Current status of ceramic injection moulding

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Historical review and introduction

In July 1938 a refractory body and method of making same were patented by the U. S. patent office. Karl Schwartzwalder claimed in his patent a method of making ceramic articles which consists in preparing a mixture of finely ground non-plastic ceramic material, and a resinous binder, forming a body from there by application of pressure, reforming said body by application of pressure and heat in sufficient degree to make the binder to flow thereby distributing the forming pressure throughout the body, permitting the body to harden and firing the hardened body to expel the binder and cause the non-plastic material to sinter together [1]. Independently from this invention, in November 1940 Klinger et al. got a German patent claiming a method of producing spark plugs by injecting a ceramic compound with addition of organic binders into a mould by application of pressure [2]. As that time, 70 years ago, ceramic injection moulding was born – a shaping method which is until today the most efficient processing route for a high throughput production of ceramic components with complex geometry. However, during the first thirty years ceramic injection moulding was of minor interest to the ceramic industry [3]. The progression into financially viability was based on research and development efforts performed during the 1970's and 1980's [4]. Only in the 1970's the growing concern over energy, environment, and natural resources increased interest in heat engines and national and international attention to the potential applications of ceramics. Injection moulding provided a cost-effective fabrication method suitable for mass production of the parts of the heat engine whose complex shape caused fabrication problems [5]. In 1984 Carborundum reported in [6] considerable effort in manufacturing development, focusing much of its energy and resources on injection moulding of turbocharger rotors. Injection moulding had enabled the company to produce such components as axial turbine blades and pre-combustion chambers. On a large scale, production included 8-inch-diameter turbine wheels for General Motors turbine engine and large static components for the automotive gas turbine programms.

Today about 330 companies from all over the world practice variants of powder injection moulding (PIM). Over 70 % of the companies practice metal injection moulding (MIM). About 5 % of the companies produce a mixture of metals, ceramics and carbide components [7]. The remaining quarter is coming from CIM. Between 2006 and 2007 the global sales growth in PIM was near 13 % [7]. In comparison to MIM ceramic injection moulding tends to have larger and higher priced components. The market for advanced ceramic products is continuously growing. The reason for this positive tendency can be seen in the unique property profile offered by ceramic materials. Ceramics are the material of choice for applications under extreme conditions, e.g. high temperatures, corrosive atmospheres, abrasive conditions or high loads at high temperatures. Moreover, ceramics combine excellent mechanical properties with a low specific weight. This combination makes them interesting as light weight construction materials for moving components in automotive, aeronautic or space applications and for engine components. Beside the so-called structural ceramics, another segment are the electronic ceramics including dielectrics, insulators, substrates, piezoelectric ceramics, superconductors, and magnets. The latter forms the largest share of advance ceramics [8].

Classification and process variants

Figure 1 shows the most efficient application areas of different ceramic shaping technologies in dependence on the number of pieces which shall be produced and the desired complexity of the component geometry. Like no other powder shaping technique ceramic injection moulding allows time and cost effective mass production of geometrically complex, net-shape components with tight tolerances [9-14]. Injection moulding offers the advantage of accomplishing ceramic parts with internal or external gears, undercuts, hollows, cross holes, and serrations without any subsequent time and cost consuming mechanical treatments [15].

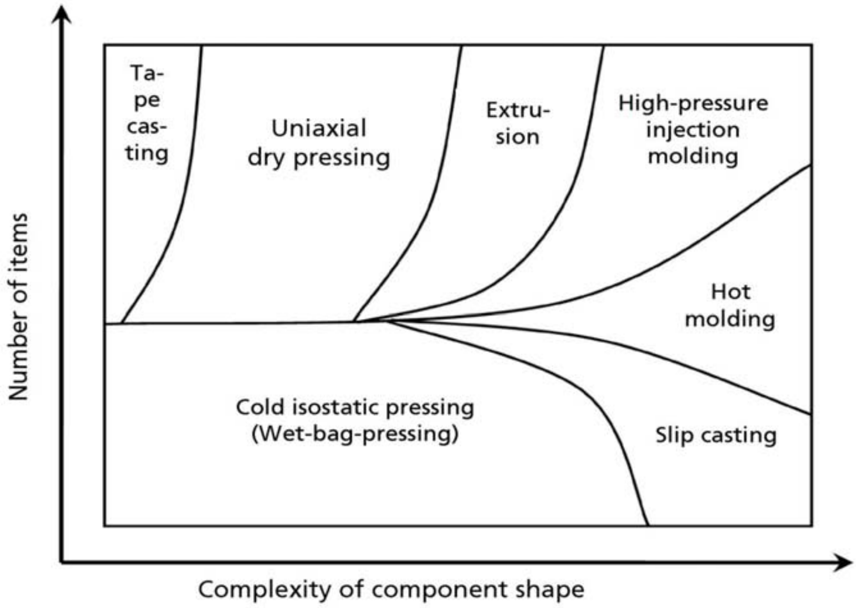

Fig. 1 Application areas of different ceramic shaping technologies in dependence on the lot size and the complexity of components geometry [16]

In contrast to raw materials used for traditional ceramics containing clay minerals and therefore showing a pseudoplastic behaviour, the initial powders for advanced ceramic products are synthetic highly pure products without any ability to plastic shaping. For that reason, these powders must be combined with organic additives giving them the desired plasticity. According to the kind of organic additive, the resulting powder-binder-mixtures, so-called feedstocks, are suited for the one or the other plastic shaping method. These methods are divided into low pressure (LCIM) and high pressure injection moulding according to the viscosity of the feedstocks and the resulting injection pressure. Applied injection pressures between 0.2 and 5 MPa are counted as the low pressure area of the injection moulding technique. For low pressure injection moulding mostly paraffin wax based binder systems are used [17- 20]. The primary advantages of low-pressure injection moulding relative to high-pressure CIM are: (1) It is a simple and low-cost process with smaller dimensions; (2) with low-pressure CIM there is less wear on the machine parts in contact with the powder batch, resulting in less contamination of the ceramic mix by metallic tooling; (3) it is easier to control the flow behaviour of the batch in LCIM; and (4) the use of LCIM eliminates the separate mixing, pelletizing and granulation steps necessary in high pressure injection moulding [18, 21]. Several disadvantages limit the use of this processing technology, in particular, defects which may remain in the moulded sintered parts. A catalogue of the defects arising from different steps of production has been reviewed by Zhang et al. [22].

Premises and technological cycle

High pressure CIM is basically borrowed from plastics industry. It can be automated easily and is therefore, like no other ceramic shaping technique, suited for large-series production. A schematic view of the processing chain of CIM is given in figure 2.

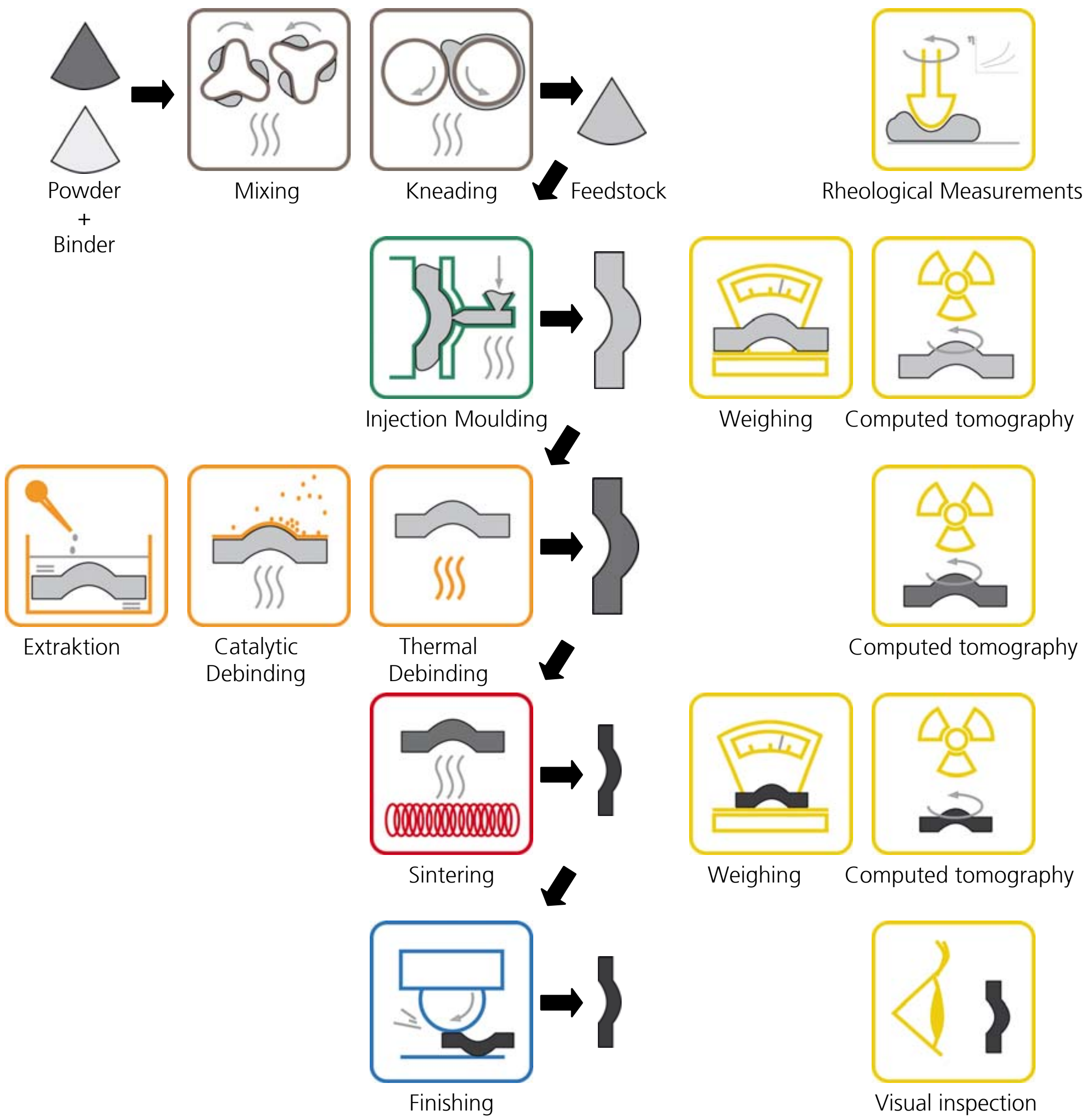

Fig. 2 Schematic view of the processing chain of ceramic injection moulding

Like for all other powder technological processing routes the choice of the ceramic powder plays a dominant role for ceramic injection moulding. Specific surface area, particle size, size distribution, and particle shape such as the purity of the powder influence the properties of the injection moulding mass, the so-called feedstock, such as the sintering behaviour and the final properties of the ceramic component. Already slight changes in the particle shape, the size distribution or the humidity of the air may influence the rheological behaviour of the feedstock [23]. Typical particle sizes in ceramic injection moulding are 1-2 µm [24], but also the use of much finer particles down to submicron or nano region have been reported [25, 26]. Besides the average particle size, the width of the particle size distribution is important. According to German [27] very wide or very narrow size distributions prove easier to mould. The feedstock for use in an injection moulding machine is a homogeneous compound of ceramic powder and a thermoplastic binder [9]. The first stage in the fabrication route requires the use of a binder system which will give suitable rheological properties to the ceramic to ensure mouldability [28]. There is considerable interest in employing formulations with the maximum volume fraction of powder in order to achieve high green density and to reduce shrinkage on subsequent sintering. Volume loadings of 50 to 70 % are desirable. Nevertheless viscosity increases considerably with increase in filler loading and therefore it is necessary to reduce the viscosity as far as possible by adding plasticizers. In injection moulding, mixing is a major factor for achieving a homogeneous powder-binder mix that is free from agglomerates, has optimum ceramic/binder content, and still maintains sufficient fluidity for moulding [3, 23, 29]. During mixing the powder particles are coated with dispersants for reducing the surface tension and after that embosomed with the binder. Deagglomeration is essential for two reasons: (1) Ceramic agglomerates function as minute porous sponges that trap the binder and (2) agglomerates function as flaw centres in final sintered components, thereby reducing product strengths and reliability [30]. The mixing or compounding process is carried out in either batch mixers, such as sigma-blade mixers, or in continuous mixers, such as single [3] and twin screw extruders [24, 31] or shear roller compactors [9, 23, 32], at temperatures above the melting points of the binder components. The twin screw extruders and shear rollers offer higher sheer rates than the batch mixers and therefore give better dispersion of the powder in the binder, but they can cause degradation of some of the binder components. Upon exiting the compounding device, the mixture is chopped into pellets or granules which are ready for delivery to the injection moulding machine.

According to [27, 33] rheological data taken during moulding are important in assuring homogeneous mixing. Torque rheometry has proven best for assessing the critical solids loadings in designing feedstock systems. However, capillary rheometry is required in determining shear rate and temperature dependent viscosity profiles. Also, these data are essential for successful computer simulation of the mould filling process. Capillary rheometry is the most accurate measuring method of the mixture homogeneity. Another method for characterising the flowability of ceramic feedstocks is the measurement of the melt flow index (MFI). Therefore the feedstock is molten at a certain temperature in a cylindrical mould and forced through a nozzle with a defined pressure. The volume passing the nozzle within 10 minutes is determined [34].

Binder systems and debinding concepts

According to Chartier et al. [35] four types of organic additives are needed to manufacture parts by injection moulding: binders, plasticizers, dispersants and lubricants. Binders give the necessary rheological behaviour to the feedstock for injection moulding and the cohesion to the green part. Plasticizers lower the viscosity of the binder to fit it to the process used. Dispersants improve the state of dispersion of the powder in the organic phase and prevent the formation of agglomerates. Finally, lubricants reduce wear between the feedstock and the tools. Polymers commonly chosen for high-pressure injection moulding are polypropylene [28], low density polyethylene [28], ethylene vinyl acetate [28], polystyrene [28], polymethyl methacrylate [36], polyvinyl buryral [36], or polyacetal [36]. As processing aid stearic acid is often applied [28]. BASF has developed a binder system which shows outstanding performance in terms of extremely short debinding times via catalytic debinding approaches, and also demonstrates excellent shape retention during both debinding phases [10, 37]. The acetal is decomposed into formaldehyde in a catalytic debinding cycle which is controlled by the use of concentrated nitric or oxalic acid. The formaldehyde is then burned off in a two stage burner to keep nitric oxides and formaldehyde exhaust at a minimum [10, 36, 38]. In [38, 39] binders based on ceramic precursors including silanes, carbosilanes, siloxanes, and silacanes are reported. Such binder systems lead to very low sintering shrinkage. During pyrolysis the ceramic precursors are converted into amorphous silicon nitride, silicon carbide or mixtures thereof. For preventing the formation of cracks, the pyrolysis must be carried out very slowly under protective atmosphere.

Several publications report feedstock systems based on carrageenan [40], cellulose derivates [41] or agar and water [31, 41-44]. Agar is the very widespread group of thermogelling polysaccharides. The water sublimes after the component has been moulded in a drying cycle, and the components are prepared for the final thermal debinding and sintering cycles. Critical issues for this system include the need of careful control of the feedstock’s environment, as the contents of water determines the flow behaviour and solids loading. The injection moulded components show a gel type of behaviour and are flexible or rubbery until they have been dried [36]. This type of binder is only used for low pressure injection moulding. In recent years, microwave drying has frequently been used; the other alternative is freeze-drying [45, 46]. Further alternative binder concepts which should be mentioned are (1) freeze-casting, where the aqueous injection moulded feedstock is frozen in the mould cavity [47], (2) hydrolysis assisted shaping of AlN by temperature induced hydrolysis [48] or (3) temperature-inverse injection moulding [49]. In the last mentioned method a cold aqueous feedstock is injected in the pre-heated mould of 80 °C. Owing to a temperature induced reaction the binder strengthens and the green component can be ejected.

Beside the above mentioned catalytical debinding in the case of polyacetal binder systems and the simple drying of components based on agar and water, thermal debinding is widely used to remove organics before sintering [14, 30, 38, 43, 50, 51]. Since thermal debinding takes place in the whole volume of the injection moulded component and decombustion products must leave the bulk by diffusion, the heating process has to be carried out very slowly for avoiding the appearance of an inner pressure which can cause cracks and voids in the debindered parts. In most cases, a mixture of waxes and polyolefins with various softening points is used in order to prevent the deformation of components during debinding. Thermal decomposition of the single components shall take place one after the other for opening pores and space for the removal of subsequent decomposition products. The binder components with higher decomposition points are called backbone polymers maintaining the mechanical stability of the injection moulded part during the debinding process. For avoiding deformation of the components occurring when the binder softens, the components can be embedded in a powder bed serving as a wicking media or they can be placed on special sintering underlays.

In order to overcome the problems in thermal debinding, solvent debinding [52, 53] has been widely adopted by industry. In the solvent debinding process, a portion of the binder can be chemically removed by using solvents like acetone, trichloroethane or heptane. A large amount of open porosities, after solvent debinding, allows the degraded products to diffuse to the surface easily [43]. A more environmental friendly method is given by binder compositions containing one water-soluble component, like polyethylene glycol, and one insoluble. Debinding takes place in two steps. In the first step, the injection moulded components are placed in water to remove the soluble component of the binder. At the same time, a system of pore channels develops which allows a relatively fast removal of the remaining component. Then the part is heated in a furnace to remove the insoluble component by thermal decomposition [38]. Solvent debinding has proven most successful in combining dimensional uniformity with reduced process times [27].

As a further alternative technique for debinding, extraction of organic binders by supercritical fluids has been investigated in [54]. Carbon dioxide is currently the most popular fluid used due to its low cost and its convenient critical temperature of 31.1 °C and its critical pressure of 7.39 MPa [55].

In spite the variety of debinding mechanisms the debinding step is the limiting factor in CIM processing. To date there has been no single debinding method that allows manufacturers to take full advantage of CIM's vast potential [30], because this processing step is the most time-consuming [56].

Injection moulding process – parameters, defects, proofing

The equipment used for moulding is a conventional injection moulding machine used in the plastics industry with small modifications to reduce wear (hardened screw and barrel) and assuring homogeneity (modification of screw design) during the plastification [24].

In principle, high-pressure ceramic injection moulding can be carried out with two types of injection moulding machines – screw machines and plunger machines. The screw machine differs from the plunger type with respect to material conveying and plasticizing [3]. In a screw machine, a major portion of heat comes from the frictional forces between screw material, and cylinder, whereas a plunger machine heats the materials by conduction and convection only. Furthermore, in a plunger machine, the pressure loss in the cylinder could be significant, and the pressure at the end of the plunger is much higher than the pressure at the nozzle.

To injection mould a ceramic part, the granuled feedstock is fed into the barrel of the machine and heated to produce a semi-fluid mass. Then the moulding medium is forced into the mould cavity through a gated runner system. In screw machines a check-ring mechanism allows the auger to act as a piston, driving the material into the mould [31]. Typically, polymer and wax-based moulding compounds are heated in the moulding machine to temperatures of 130 – 200 °C and are injected using barrel pressures between 50 and 150 MPa. Defects which result from the injection moulding process are later not reparable and impair the quality of the ceramic components. A catalogue of the most frequent defects which may arise during ceramic injection moulding has been compiled by

Zhang et al. [22]. Moreover, a comprehensive overview over injection moulding errors, their sources and helpful counteractions are given in [13]. First qualitatively perfect appearing green parts can also possess internal stresses, which may lead to cracks in further process steps like debinding. Therefore, local shrinkage differences should be avoided. For that purpose the use of a hot runner system has been proved to be promising [57]. Material cannot only be saved by hot runner technique, but also manufacturing of less stress parts can be achieved [58].
Because of the abrasive properties of the ceramic powders the choice of suited hardened steel plays an important role for tool construction. For tool designing the geometry of the components and the lot size are the crucial aspects. They affect the position of the component in the tool and the number of cavities, the design of the runner system, the type and the position of the sprue, the operating mode, the removal of the injection moulded parts (manually or automated) such as the ejection system (mould parting surface, slides, core pullers) [59].
Depending on the material, the powder packing density achieved by the solid volume content of the feedstocks, the powder particle size, shape and size distribution, the moulded ceramic green parts are typically 14-22 % larger (linear) than the sintered components owing to the shrinkage during sintering. This property of ceramic injection moulding has to be taken into consideration as an oversize factor for tool construction.
Quality control of ceramic components in the green, in the debindered and in the sintered state is commonly carried out by weighing and by visual inspection. Combining both simple methods allow to detect surface cracks, impurities, pores, voids, distortions, incomplete parts or sink marks. Measuring the density of the ceramic components after sintering is another indispensible method for characterising the performance of the injection moulded part, because most of the defects introduced in the green body during injection moulding either increase or even become obvious after sintering. A more precise method for detecting deviations from the desired geometry or distortion of components offers the 3D coordinate measuring technique [26]. For detecting defects inside the components already in the green state computed tomography [26, 60] is the non-destructive method of choice. By means of computed tomography entrapped air, voids, cracks, pores, inclusions, impurities, but also weld lines, powder-binder-separations and density inhomogeneities [61] can be discovered in this early processing state.

Micro PIM

Besides the distinction between high pressure and low pressure ceramic injection moulding a lot of special methods can be derived from the injection moulding process. One method – named after the size of the injection moulded parts – is micro ceramic injection moulding (MicroCIM). MicroCIM can be carried out either as high pressure [62, 63] or low pressure method [20, 64, 65] depending on the binder system. Intricate components with 18-µm features, including through holes, gear teeth, and screw threads, are well suited for MicroCIM moulding. MicroCIM parts weighing as little as 0.0004 g serve in a wide variety of applications where high temperatures and caustic environments preclude most metals and engineered thermoplastics [66]. Micro related products can be used in the fields of information and communication technology, medical and biotechnology, such as micro-sensor and micro-actor technology [67]. MicroCIM allows the manufacturing of precision products characterized by minimal wall thicknesses of 20 µm, aspect ratios up to 20 or structural details in the range of 50 µm or in certain cases less than 20 µm and a surface roughness of about $R_z < 0.05$ µm [68- 71]. Good examples of micro injection moulded devices are multi fiber connectors with 16 multimode channels or containers for 3D cell culture systems using micromechanically cut mould inserts. For the adaption of the process to micro manufacturing, however, additional features had to be developed and implemented. Although there is a relatively wide range of materials available for PIM, it is necessary to focus on powders of small particle size. The initial powder requirements for MicroPIM are more stringent than that for conventional PIM. The powder must be homogeneous; and the grain size of the sintered part should be at least about one order of magnitude smaller than the minimum internal dimensions of the micro-component, in order to obtain a fairly isotropic behaviour [67, 72]. With respect to the surface quality of the replicated structures, best results have been achieved by using ceramic powders with a mean particle diameter of 0.5 µm or even smaller. Therefore, the demand to process finer powders including even the utilization of nano powders can be regarded as one of the

most important results of the investigations carried out up to now in MicroCIM [73]. For attaining a viscosity of the plastic melt which is low enough to fill even smallest structural details down to the submicrometer range a so-called variotherm temperature conduct is used for heating the moulding tool near the melting point of the feedstock prior to its injection into the tool [73, 74]. Due to the high fragility of most microstructures, highly precise tool movements have to be assured in MicroCIM. For allowing the injection process to be accelerated or slowed down in a controlled way, by means of ramps injection moulding machines with position regulated screws have been developed [63]. Moreover, micro components are considerably different to handle from macroscopic components, for instance in micro dimensions, electrostatic forces exceed the gravitation force so that micro parts sometimes stick to handling systems instead of dropping. Alternatives to MicroCIM are rare. LIGA techniques are usually only suitable for 2D geometries, and most of the techniques are too expensive to become cost-effective in the near future [75]. Good examples of ceramic micro components are a cogwheel for micro motors which has been manufactured by means of fully-automatic series production of CIM moulding process and a ferrule with a through hole diameter of 125 µm [63].
For improving the precision and the acutance of surface micro structures such as the homogeneity of injection moulded parts the shaping process can also be carried out as injection compression moulding. This means, after injecting the feedstock in the mould cavity the tool is compressed by a stroke of 0.2 to 0.3 mm providing an additional embossing step.

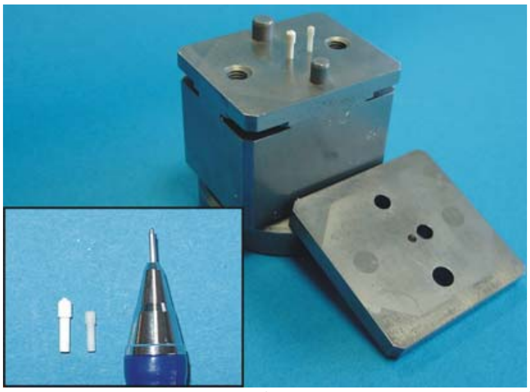

Fig. 3 Nozzle body for cooling systems of power stations with hot moulding tool (source: MicroCeram GmbH)

Fig. 4 Advanced ceramic components made by micro-injection moulding (source: Rauschert Heinersdorf-Pressig GmbH)

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Multicomponent PIM

However, micro components are not only becoming ever smaller, they are also required to have several functions at one time [63]. This trend can also be predicted for advanced ceramic macro components. First ideas and patents concerning co-injection moulding of two synthetic materials appeared 40 years ago [76]. To the first applications of two-colour injection moulding belong buttons with abrasion-resistant symbols for computer keyboards or telephones [77]. Indeed, applications from the automotive branch show that co-injection moulding is applied to a great variety of automotive components. By this technique not only different colours but also thermal, mechanical, electrical and optical properties of plastics can be combined in one processing step [77].

In the mid 1990s multi-component injection moulding has been applied to PIM technology since the ability to manufacture and surface engineer a component in a single process has attractive implications, both technically and financially, particularly when large numbers of complex shaped components are to be produced [78]. First research results have shown that ceramic materials can be combined in one part by 2C-CIM [78- 80]. Following model systems have been produced: (1) a component with alumina skin and core, possessing a 0.5-µm particle size skin layer surrounding a 1-µm particulate core [78], (2) toughened components with a skin containing 20 vol.-% partially stabilised zirconia surrounding a 100% alumina core [79] and (3) a ceramic heater consisting of different Al_2O_3/TiN-mixed ceramics [80]. Moreover, the combination of different ceramic materials and ceramics with metals by two-component injection moulding is described in [81]. By systematical combining ceramic and metal powder components via two-component injection moulding, new and highly functional composites with property combinations like conductive/insulating, magnetic/non-magnetic, thermal conductive/thermal insulating or ductile/hard are achievable [82].

All studies on 2C-CIM have disclosed that sintering rate control is crucial to the success of this shaping method. Both components must sinter at similar rates and at similar positions in the sintering temperature profile to avoid delaminations. The sintering behaviour can be altered by lowering the powder content of one mix and hence its green density, at the risk of a porous component, or by addition of a second non-sintering composite phase [78]. The variety and combination of materials that can be used in the manufacture of metal or ceramic components by powder co-injection moulding is more limited due to the requirement for compatible sintering characteristics [78]. Depending on the design and size of the contact area of both ceramic materials the feedstock components can be injected simultaneously or sequentially. A quick succession of the injection processes is essential for a high compound strength [80].

In order to be successful in two-component powder injection moulding it is essential to develop feedstocks with comparable shrinkage rates during co-debinding and co-sintering of the injection moulded material compounds. The absolute shrinkage during sintering depends on the solid content of the feedstock, i.e. the green packing density of the powder. Furthermore, the shrinking behaviour of the powders is influenced by the type of the ceramic powder used and its particle size distribution [60]. For achieving defect-free material compounds after the thermal treatment it is necessary that the onset of shrinkage of both materials is comparable and that the thermal expansion coefficient of the ceramic materials is almost the same. The last mentioned criterion is decisive during cooling of the material compound after sintering for preventing high cooling stresses. Moreover, a similar thermal expansion coefficient would be crucial for surviving cyclic heating and cooling of the compound during application [26].

Fig. 5 Ceramic gear wheel in the green and sintered state made by two-component CIM combining alumina and zirconia toughened alumina (source: Fraunhofer IKTS, Designed by Robert Bosch GmbH)

The large-scale production of multifunctional components with complex geometries is also the goal of a further process variant – the so-called inmould labelling where ceramic injection moulding is applied to complete several inserts like ceramic or metallic green tapes [83, 84] or green components. Inmould-labelling combines shaping methods like tape casting with injection moulding and offers some additional process-relevant advantages: (1) Very thin functional layers can be realized; (2) intermediate layers improve the material composite and facilitate transitions in thermal expansion behaviour, and (3) extremely high aspect ratios can be obtained within the composite. In [82 and 85] stainless steel and yttrium-stabilized zirconia have been chosen as material combination and could be successfully combined by inmould-labelling such as by two-component injection moulding.

Fig. 6 Thread stopper (source: Fraunhofer IKTS, Designed by Rauschert Heinersdorf-Pressig GmbH)

Special process variants

A further important method of ceramic injection moulding has been described in [86; 87]. Since the size of injection moulded parts is limited by economic efficiency due to the expensive powders needed as well as the time required for the debinding of the parts with high wall thickness the combination of CIM with gas-assisted injection moulding is of great importance. The gas-assisted powder injection moulding (GAPIM) can be subdivided into two different processes, the full shot and the short shot process. Using the full shot process, the gas is injected when the cavity is filled completely with melt. The injected gas pressure forms a bubble in the inner core by pressing the melt into an additional cavity. In the short shot process the gas is injected into the partly filled cavity. The gas presses the melt to the end of the cavity. When processing ceramic feedstocks by GAPIM, time and costs can be saved in the debinding step. On the other hand, parts of high geometrical complexity used to pipe corrosive media, media under high pressure or temperature can be produced in an automated way. The use of GAPIM is described in literature for alumina and silicon nitride ceramics [87].

For continuous or semi-continuous production of ceramic parts extrusion is very interesting because of the relative simplicity of the equipment. All type of plasticized material can be extruded by pressing them through the orifice of a die. Therefore, for thermoplastic extrusion of ceramic bodies in principle the same polymer binders, plasticizers, surfactants and sliding agents known for ceramic injection moulding can be used [88]. Typical products are thin walled-tubes [89], pipes, or fibers.

Selected CIM products

Type of component	Ceramic material	References
• Engine components / Engineering		
water pump seals [90]	SiC	
Nozzles, guides, gear wheels, screw threads Stators Precision dispension nozzles Sensor covers Tooth belt wheel Sensor tubes Bearings Seals Scissors Micro electrodes for ultrasonic welding Drill bits	 Si_3N_4 Al_2O_3 Al_2O_3 Al_2O_3 Mg-stabilized ZrO_2 Al_2O_3	 [69] [31] [66] [66] [91] [19] [14] [14] [14] [20] [24]
• Textile industry		
Wire guides Textile thread guides Twist stopper	Al_2O_3 Al_2O_3, SiC ZrO_2/Stainless steel	[66, 14] [66, 18, 92] [84]
• Medical/Dental applications		
Orthodontic brackets Dental implants Prosthetic replacements Abutments Endoscopic tools Tweezers	Al_2O_3 Al_2O_3 Al_2O_3	[66, 69] [66] [93] [69] [69] [10]
• Watches/Jewelery		
Precision watch gears Watchcases	Al_2O_3 ZrO_2	[66] [14]
• Communication		
Ferrules Optical sleeves Soft magnetic components	ZrO_2 ZrO_2 Mn-Zn ferrite	[94, 9] [94, 95] [96]
• Exhaust system components		
oxygen sensor components	ZrO_2	[90, 31]
• Metallurgy		
Ceramic casting cores	Al_2O_3/ZrO_2 SiO_2	[97, 24]
• Automotive components		
Valve components Turbocharger rotors Swirl chambers for high power turbocharged diesel engines Radial rotors with integrated ceramic shaft Airbag components Glow plug for diesel engines Gear wheel for fuel pumps Valve seat	Al_2O_3, Si_3N_4 SiC Si_3N_4 SiC Si_3N_4 + $MoSi_2$ Al_2O_3/ zirconia toughened alumina (ZTA) Si_3N_4/SiAlON	[15, 98] [6] [99] [100] [24] [60] [60] [60]
• Electrical components		

Electrical components for automotive exhaust RF and electrical insulators Microwave dielectric components Electrical micro heater Cooling socket for electronic components Heat sinks, electronic packages,	Al_2O_3, steatite Al_2O_3 $Ba(Zn_{1/3}Ta_{2/3})O_3$ Al_2O_3/TiN AlN	 [101] [66] [102] [80] [92], [24]
• Home appliance and office equipment		
Injector for percolators Cups Printer head, disc drive rocker arm, camera components, micro gears in electrical toothbrush Pepper mill grinding gears Inkjet printheads Back cover of mobile phones	ZrO_2 Porcelains Al_2O_3 Al_2O_3 ZrO_2 (black)	[103] [42] [24] [104] [105] [37]

Fig. 7 Watch lunette (source: BRÖLL GmbH)

Fig. 8 Electrically conductive CIM part made of TiO_2, embedded in an injection-moulded plastic assembly (source: Kläger Spritzguss GmbH & Co. KG)


Fig. 9 Thread guide (source: BRÖLL GmbH)

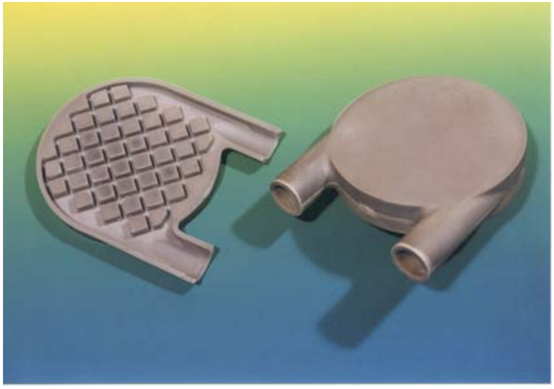
Fig. 10 Cooling box for electrical components (source: Fraunhofer IKTS)

Summary and outlook
According to [106] major growth areas in PIM in the coming years can be seen in multi-component PIM and MicroPIM. Multi-component PIM enables several different materials to be combined in a single component, although the difficulties lie in the combination of the physical properties of the various materials. In the case of MicroPIM the challenge is to develop a suitable feedstock and high-precision, miniaturised mould cavities. The fully automatic process for removing the micro components also represents an enormous technical challenge. For industry, process optimisation and cost-reduction are of great concern. Universities and research centres efforts are focused on computer modelling of moulding, debinding, and sintering. Computer simulation of the PIM process to predict size, shape, defects, and to properly design tool and production operations is a major activity. Another goal is the production of very small medical and computer devices using fine-grained powders [4].

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