

Production Quantity vs. Component Design – Where's the Optimum

How to cost-optimize the design of a ceramic component? A truly complex problem, which includes mould and assembly costs, mould lifetime – in general manufacturing costs, but also component design and choice of the ceramic material.

Introduction

Users who utilize components made from technical ceramics in their devices or assemblies often wonder how to cost-optimize the design of the component – this is a truly complex problem as it needs to focus not only on the very low unit costs of the ceramic component, but also needs to take into consideration issues relating to the assembly costs when installing the component, the cost of repairs or exchanges (for wearing parts) if applicable, as well as the initial mould costs. It may also be necessary to consider recurring refurbishment costs for the mould used to produce the ceramic part, as many ceramic materials are very abrasive and certain parts of the mould will need to be replaced at regular intervals. It is therefore advisable to involve the manufacturer of the ceramic part very early in the piece, and to collaboratively develop the ceramic component in a spirit of cooperation and trust.

Depending on the selected or jointly developed design of the component, the choice of ceramic material, and the total required quantity, a cost-optimized process for forming the component can be determined; as the required quantity can in many cases be very speculative, it makes sense to work with a ceramic manufacturer that has a wide range of forming processes at its disposal and, in the event that the quantities change (increase), is able to offer a suitable alternative forming process.

Keywords

cost factors, material selection, manufacturing methods, component design

Cost factors in ceramic production

The cost factors in ceramic production processes are many and varied and, depending on the selected conditions, can vary by more than several orders of magnitude. In general, the factors of greater or lesser importance in the production of technical ceramics are as follows:

- **Raw material costs:** these include the costs of preparing the formable compounds from the usually powdery raw materials, whereby associated labour and energy costs, equipment depreciation, repair and maintenance costs, costs for quality assurance, etc. should be factored in as well. This makes it possible to directly compare ready-to-process compounds purchased from external suppliers with batches of compound prepared in-house. Many manufacturers of technical ceramics place great importance on performing this raw material preparation themselves, either entirely or at least the important parts of the process, so as to have better control over the quality, and to be able to respond more flexibly to customer requests. Even though, due to the smaller scale equipment used, it is often disadvantageous from a purely cost-based perspective to carry out the raw material preparation in-house rather than purchasing the compound from external suppliers, this is often more than compensated for by tighter tolerances for the compound and greater flexibility, however this can be difficult to put into hard figures from a commercial point of view.
- **Direct labour costs:** these are the labour costs directly attributable to the production of the product, that is, the labour

costs for the unskilled or skilled worker carrying out work on the ceramic part. This can clearly vary greatly depending on the country in which the item is produced.

- **Indirect labour costs:** costs for machine setters, assistants, etc. involved in supporting processes associated with the production of the product but not directly involved in the production process. These costs may, for example, be reported under setup costs.
- **Energy costs:** the largest portion of the energy costs in ceramic production is associated with the firing process and, if applicable, also the thermal debinding process, regardless of whether fossil fuel-fired kilns or an electrically-heated kilns are used. The proportion of the energy costs for forming and other processes is usually negligible compared to the energy costs for the other manufacturing steps. The required firing temperature depends on the material used, the duration of the firing process, the maximum heating capacity of the kiln and, in particular, the size of the component as large-volume components required a longer heat treatment processes than small parts.
- **Mould costs:** since ceramic components are produced in an initial forming process, they require the use of moulds. The costs and downtimes for these

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types of mould can differ greatly, from costs of under EUR 1000 for simple extrusion dies, to two-digit thousand Euros for simple injection moulds or tools for pressing, or well up into the price range of a mid-class automobile for complex injection or extrusion moulds (e.g. for producing honeycombs in the latter case). The service life depends on the material used (steatite, for example, is less abrasive than alumina) and the mould material used (hard metal or steel).

- **Overheads:** This includes the costs for supporting processes such as purchasing, quality assurance, sales, maintenance, etc. as well as facilities management and rent, depreciation etc.
- **Profit:** Any business enterprise is only viable if it can generate a profit that can be reinvested, for example, in new developments, equipment, etc.

Depending on the approach, it also possible to group the cost factors differently, or categorize them in greater detail, but the total cost will, of course, be the same in the end.

Material selection

The collaboration between the ceramics user and ceramic manufacturer usually begins with the selection of a material that meets the requirements.

The customer, in collaboration with the ceramic manufacturer, first needs to define the requirements profile for the ceramic material; this involves, for example, obtaining answers to the following questions:

- **What loads/forces will act on which locations on the ceramic part?** How are the forces applied? Will the part be subjected to impact loads or shocks, or slow increases in force? Note: From a design perspective, ceramics should be subjected to compressive, not tensile or bending forces, and the application of point loads must be avoided.
- **What temperature range will the component be exposed to in use?** What rates of heating or cooling will it experience? Note: Localized heating or cooling should be avoided.
- **Could assembly stresses arise in use?** For applications with temperature changes, it may be necessary to select a ceramic with a similar coefficient of

thermal expansion to the connecting materials in order to minimize thermal stresses.

- **Will the part come into contact with corrosive media such as acids or alkalis?** The application temperature is important in this case too. Ceramics are usually very resistant to organic solvents.
- **Does the ceramic need to be thermally insulating, have a good thermal conductivity, or is this property not relevant to the application?** Does its specific heat capacity matter? In this case, too, the application temperature plays a role because these material properties are temperature dependent.
- **If the density, and therefore the weight, is important and the objective is to save weight,** silicate ceramics or silicon nitride can be used; if high densities are required (e.g. grinding media), then zirconias would be suitable.
- **If relevant: What electrical properties are required?** Electrically insulative, semi-conductive or electrically conductive? Do more complex requirements exist, for example a high or low dielectric constant, a low loss factor in high frequency applications, etc.

The present article will not go into detail about all types of ceramic materials, but rather provide a short overview of the most important materials and their most important properties:

Silicate ceramic materials such as porcelain, steatite, cordierite (dense or porous) or mullite: This group of materials tends to have the lowest raw material costs of all the technical ceramic materials because they are based on specially prepared natural raw materials. The strength level of these materials is relatively low but more than adequate for many applications (typically from 15–30 MPa for porous cordierite (C511, C520 and C530), over 60 to 160 MPa for porcelains, dense cordierite C410 and mullite C610/C620, and up to 140 MPa for steatite C221). Due to their relatively low firing temperatures in the range of approx 1250 to 1400 °C and their favourable raw material costs, these materials are still very important these days in terms of tonnage. The advantages of cordierite materials come to the fore for parts subjected to thermal shock loads, in high temperature applications, and where

a good thermal insulating capacity is required.

Oxide ceramic materials, the main examples of which are alumina and the zirconias as well as the ZTA (zirconia-toughened alumina) or ATZ (alumina-toughened zirconia) composites. These materials have a much higher strength level than the silicate ceramic materials, whereby alumina with a strength of 300 to 600 MPa is used for moderate loads, and zirconia for high loads as the Y-TZP variant can reach a strength of 1200 MPa. The cost advantage in terms of raw material costs of alumina (EUR 3–10/kg, only rarely above EUR 100/kg) compared to zirconias (mechanically reliable variants typically cost around EUR 30–EUR 120/kg) explains the widespread use of these materials in components that are subject to mechanical loads.

The advantages of partially stabilized zirconia come to the fore in applications where a high fracture toughness under load is important; alumina, on the other hand, with a thermal conductivity of approx 25 W/m-K is a much better heat conductor than zirconia (2–3 W/m-K). Where ionic conductivity is required (e.g. in lambda probes or fuel cells), a fully stabilized zirconia can be used.

Non-oxide ceramics are represented by the nitrides (mainly silicon nitride and aluminum nitride) and carbides (silicon carbide or, for example, boron carbide). The carbide materials are characterized by their high hardness and stiffness, silicon nitride exhibits mechanical properties almost equal to that of zirconia however its density, at approx 3,2 g/cm³, is significantly lower which can be advantageous in certain applications.

For known traditional applications there are specific materials that have been used for many years and, in most cases, there is no reason to deviate from these as they already represent the optimal solution. Steatite C221, for example, is a tried-and-proven material for low-voltage high-power fuse bodies (in smaller sizes) as it is well suited to dry pressing, which is a relatively economical process and therefore ideal for use in the mass production of millions of fuse bodies/year. The strength level of this material is more than adequate for most applications; a mullite material (C610, C620, C780 or C786) can be used where

more stringent requirements on strength apply, or cordierite C410 where more stringent requirements on thermal shock resistance apply.

The material steatite C221 is also well suited for complex sockets, housings, plugs, etc. that are required in large quantities and therefore need to be manufactured by means of the dry pressing process – it has been used in these kinds of application for many decades now.

Due to its high hardness (Mohs hardness: 9), alumina is commonly used in wear protection applications in the textile industry, in wire manufacturing, and in other applications where resistance to abrasive loads is required. A further established application for alumina materials is in temperature measurement technologies. Thanks to its good chemical resistance and good electrical insulating capacity at high temperatures, along with its inert behaviour towards typical thermoelement alloys, alumina is used to manufacture the capillaries and protection tubes for these technologies and, in many cases, has already been in use for many years. In order to withstand the specific stresses that arise in use, the materials used for temperature measurement technologies require a different structure, however, than those for wear protection applications – even though the alumina used in both cases has a comparable level of purity.

Forming method, design and production quantity

A wide variety of forming methods are available in ceramic production, which, depending on the necessary/desired geometry and the required quantities of the item to be made out of the technical ceramic, provide a cost-optimized solution within a certain range (Fig. 1). When investigating different design variants, the user of the component also needs to take into consideration the assembly costs and, if applicable, any difference in cost in the required connecting components. It is therefore useful to work with a ceramic manufacturer who, besides offering a diverse portfolio of materials, will have a wide range of forming processes at their disposal to support different design variants, and be able to provide a single-source solution from prototyping right through to high-volume production.

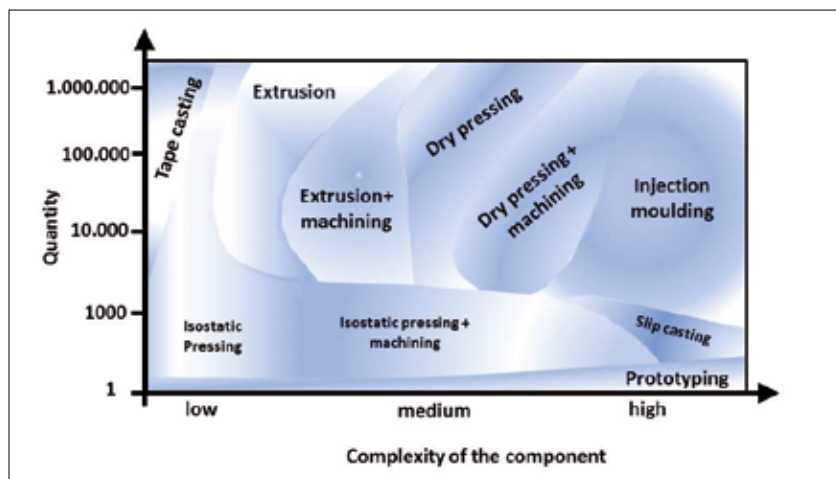


Fig. 1
Shaping technologies are dependent on complexity of the components and the quantities needed

This enables the experience gained from prototype production to benefit volume production as well, and also ensures the prototypes are suitably designed from the outset for later full-scale production using a different, mass production suitable forming method – and this is where the devil often lies in the smallest details.

We will now briefly discuss the most common forming methods and their typical applications and limitations:

Prototyping methods: these are especially suitable for producing small or very small quantities, either because only a small number of components are required for the application, or when performing feasibility testing on the components under near-production conditions prior to investing in a mould. A widely used method is the machining of pressed blanks in an unfired or semi-fired state or, where tight tolerance limits apply, in a fired state. The significant improvements in printing processes in recent years have further expanded the possibilities in this area; this method also offers the ability to incorporate undercuts or cavities into the components, which would either not be possible at all, or only possible at considerable expense using other forming methods. These options significantly extend the cost-optimal range of printing processes, and open up completely new, previously unimagined design possibilities for ceramic components. Common to all prototyping methods is that they typically do not require a mould, so the initial costs are restricted to

just setup and programming costs. These methods have a limited ability to produce large wall thicknesses in the case of the printing processes, or to incorporate holes that are both small and deep. The latter is much easier to achieve, for example, by extrusion. The prerequisite is that the material to be machined is available in a pressable form (usually not a problem), or in the case of the printing processes that the material is available in a suitable form for the printer being used (e.g. photosensitive slurry). The commonly used materials are generally available in these forms, and the others will also become available over time if sufficient demand exists.

Tape casting: in this case thin tapes of a defined thickness are continuously cast and dried on a carrier tape. Larger quantities of the item can be punched out in the green state and then sintered if the required tolerances allow this. Smaller quantities or tighter tolerances can be achieved by laser cutting in the fired state. The maximum thickness is limited to approx 1,5 mm in this process, however thicker components can be obtained by laminating together several tapes. This process is therefore ideal for thin, flat components that are required in medium to large quantities.

Isostatic pressing can be used to produce tubular or rod-shaped components of low to medium complexity. Particularly worth mentioning here is the very high, low-defect and uniform compaction that can

be achieved, which can be a requirement for components subjected to high levels of stress. Components of greater complexity can be achieved by combining isostatic pressing with machining.

The cost of a product-specific pressing mould can range from under EUR 1000 to, in rare cases, EUR 10 000. Most ceramic manufacturers have a set of standard moulds for one-offs or very small runs; the green bodies produced with these then need to be machined to the final shape, which results in large losses of material. In the case of expensive raw materials, investment in a near-final-shape, product-specific compression mould can be worthwhile even for low quantities.

Extrusion is the preferred method for producing long rods or tubes, including with complex internal or external geometries, and even small lengthwise holes of, e.g. 0.2 mm diameter can be achieved. The ceramic raw material is first brought into a workable form through the addition of an organic additive and solvent (usually water), and is then formed into the desired shape by passing it through the die of an extruder.

The cost of the mould is fairly minimal at several EUR 100 for very simple rods to single-digit thousand Euros, but can climb to significantly higher than EUR 10 000, however, in the case of moulds used to extrude honeycombs. This method can be used to produce very long components, and the limitations arise more from the size of the kilns or kiln furniture and the mechanical stability of the component rather than the actual forming process.

A disadvantage is that it does not allow any changes in cross-section during forming; in special cases these could be incorporated by further processing in the unfired state, which would then enable more complex components to be produced. Extruding is suitable for medium to very large quantities in industrial applications.

Dry pressing offers the ability to economically produce medium to very large quantities of quite complex shaped items. It is also able to produce large, flat components with a thickness, however, that is greater than what can be achieved with tape casting.

Depending on the size of the component, it is also possible to use multi-cavity moulds; the company Rauschert has suc-

cessfully implemented several 32-cavity moulds. It must be noted, however, that the cost of a complex multi-cavity mould can easily approach that of a mid-class automobile, nevertheless this process is widely employed for those sorts of items that have a high long-term demand.

Before being used in the dry pressing process, the ceramic raw material needs to be brought into a free-flowing form, usually by spray drying, to enable the mould to be filled quickly and uniformly with the ceramic raw material. After mould filling, the raw material is compacted at pressures of 300–500 kg/cm² (silicate ceramics) to 1200 kg/cm² (oxide ceramics). After compaction, the components are pushed out of the mould by ejector pins.

A new cycle begins with the injection of more compound. This method is subject to the following limitations: the maximum possible height of the component depends, more or less, on the physical size of the press, small holes of only a short depth can be produced, and there is only a very limited ability to incorporate cross-sectional changes through the use of lateral slides, provided the ceramic material has sufficiently good glide properties.

More complex components can be produced by subsequent further processing in the unfired state, or by fully automated linked operations in the case of large volume production.

Small to medium quantities of quite complex geometries can be produced by means of *slip casting*. As this process is very difficult to automate, there is a limit on the quantities that can be produced economically, however it can be justified on the basis of the fairly low mould costs. Tight tolerances are very difficult to achieve due to the high shrinkage. To produce items by this method, the raw material needs to be made into a liquid suspension (called a slip) with the aid of organic additives such as dispersants, binders, floating agents and anti-foaming agents.

This is then poured into a porous plaster mould that draws the water out of the slip through capillary action, thereby forming a cast on the mould surface that corresponds to the item being produced. After removal from the mould the item is dried and then fired. Due to the long cycle time of several minutes to even hours, it is necessary to either use many moulds at the

same time, or perform frequent castings. This process is well suited for the production of medium to large components, but has disadvantages for very small components.

Medium to large quantities of complex components can be produced economically by means of *injection moulding*. In this case the ceramic material is brought into an injection mouldable form through the addition of thermoplastic binding agents, and then processed on specially hardened injection moulding machines in a similar manner to plastics injection moulding. Next the thermoplastic binding agents are removed again by means of solvents or a thermal process, and the component is then sintered.

The full spectrum of injection moulding processes can be employed to produce very complex components. Cross holes can be incorporated by means of lateral slides, undercuts by means of collapsible cores. This process has disadvantages in the case of large wall thicknesses as it is very difficult to avoid cracks during debinding. Thermal debinding processes can take several days or even up to a week, which results in a long overall processing time from forming to the finished part.

The mould costs may in rare cases come out at just under EUR 10 000 but can also extend to significantly above EUR 20 000. The preparation of the injection moulding compound from the ceramic powder is a cost factor that should not be underestimated.

This is compensated for, in particular in the case of smaller items with a low component weight (low proportion of raw material costs), by the greater design possibilities and near-final-shape forming.

Through a close and trusting collaboration between the customer and ceramic manufacturer, it is possible in most cases to come up with a cost-optimized solution from the wide variety of options available.

Case studies

Now provide a couple of case studies are provided in which several possible solutions are presented by way of example and compared with one another.

The requirement was for an insulator with a brass bushing glued into both ends and able to insulate an electrical voltage of

40 kV (Fig. 2). Pressure loads in the axial direction, maximum temperature in use approx 70 °C. Smooth surface so no dirt can settle on it and lead to leakage currents or spark-overs on the surface, no corrosive loads from acids or alkalis. Based on this information, steatite was selected as a mechanically and electrically suitable material. To prevent contamination on the surface, it was proposed to glaze the item. For the forming process, comparative calculations were performed for isostatic pressing and white machining of rods versus extrusion followed by white machining of rods (Fig. 3). In the case of isostatic pressing, the blind holes to accommodate the threaded bushings can already be incorporated during forming.

After pressing, it is therefore only necessary to machine the circumference to incorporate the grooves. This is then followed by firing, glazing and glaze firing. In a final work operation the threaded bushes made of brass are glued into the blind holes.

The total costs for the production of the compression mould, the fixtures for white machining, and the grinding wheels is EUR 8000. For extruding, the mould costs are reduced to EUR 250 for the fixtures for white machining and the grinding wheels, and the blanks can be produced from a standard mould. If an extrusion mould had been required, then the costs would still have been in the order of EUR 1000. Unlike isostatic pressing, it would still be necessary in this case to incorporate the blind holes in both ends after trimming the dried, extruded rod. Only after this can the cylinder surface be profiled as in the isostatic pressing case. From this process step onwards the production process is identical and there are no differences in terms of cost.

For isostatic pressing the initial costs are higher, however the unit cost and, to a less extent, the raw material usage are lower (though this is less of a factor for the rather inexpensive steatite material) as the blind holes are already incorporated into both ends during forming.

This gives a break even point of approx 10 000 units for this item. As the demand from the customer was relatively low and it was not possible to predict the future demand, it was arranged to produce the item by extrusion combined with machining in the unfired state.

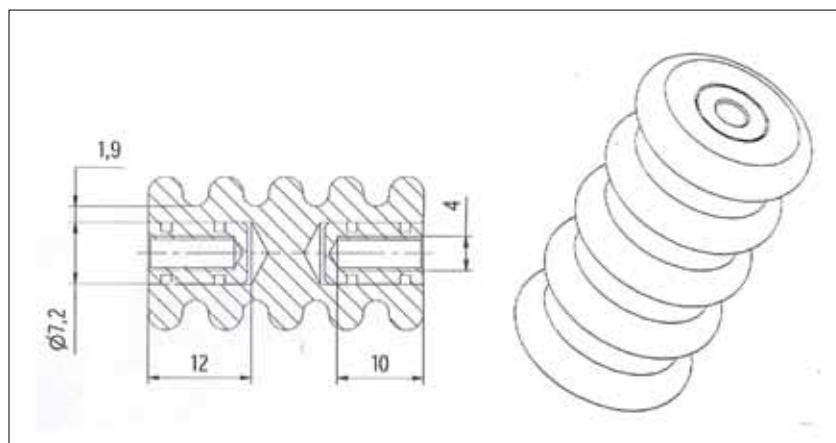


Fig. 2
Insulator with a brass bushing glued into both ends

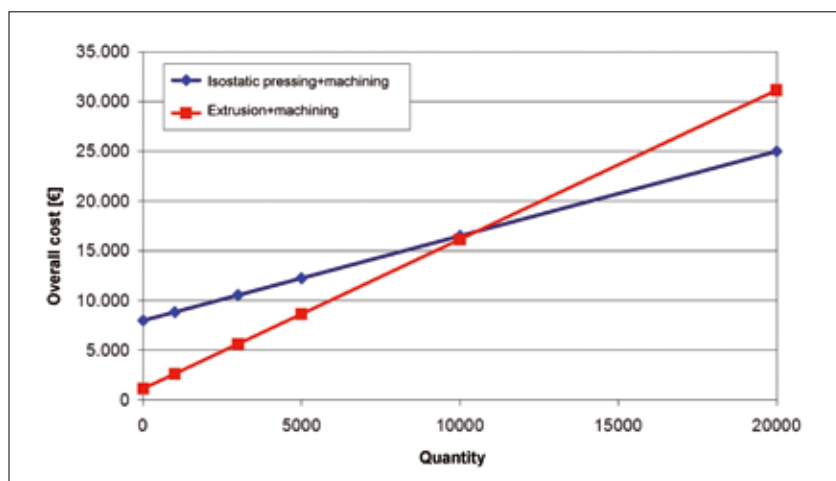


Fig. 3
Cost assessment extrusion and isostatic pressing including machining dependent on quantities of components to be produced

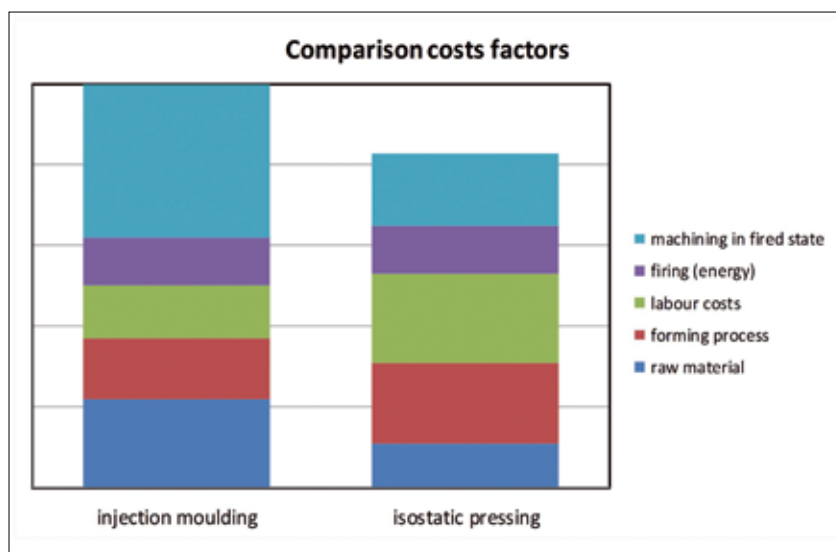


Fig. 4 Comparison of costs isostatic pressing vs. injection moulding

Valve component with tight tolerance for the internal diameter

In another case there was a requirement for large quantities of a sleeve made from alumina for incorporation into a dosing valve.

Due to the method of operation of this valve, it was necessary to precisely control the internal diameter within a tolerance range of $\pm 0,01$ mm (process reliability was guaranteed by SPC). Given the complex external geometry and various radial drill holes, the item was initially produced by injection moulding. After firing, the internal diameter was honed in a two-stage process to meet the required tolerance limits.

Due to firing distortion and shrinkage variations, it was necessary to add a grinding allowance of max. 0,3 mm to the internal diameter, which then needed to be ground in a two-step hard machining process. By completely converting the production

process from injection moulding to isostatic pressing followed by white machining, considerable savings were able to be achieved (Fig. 4). This enabled the grinding allowance to be reduced to max. 0,15 mm, thus requiring only a single-step hard machining operation.

The lower costs for hard machining and raw materials more than compensated for the significantly higher cost of the forming process, thereby enabling a bottom line saving of approx 15 % to be achieved. The throughput time was also reduced by approx. 30 %.

Summary

The varied and complex interdependencies between the different materials, forming methods and production quantity requirements have been described here.

When the required quantities are known and a material has been selected, it is possible in many cases to define a cost-

optimized manufacturing route for a desired geometry.

The crucial element with regards to the manufacturing route is the selection of the forming method, which will determine the required upstream and downstream work operations.

It should be noted that it is not always possible to produce every desired geometry using ceramics; not everything that can be manufactured from plastic or metal can also be (viably) manufactured from a ceramic material.

Collaborating with a ceramic manufacturer with a wide range of forming processes at its disposal gives users the necessary flexibility to respond to any increases in product demand, and the ability to purchase their product from a single supplier, from early prototypes with no mould costs right through to high-volume production. This reduces development times and avoids duplication of work.



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