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# RESEARCH ARTICLE

## A STUDY OF CERAMIC CORE FOR GEOMETRICALLY COMPLEX INVESTMENT CASTING

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**ABSTRACT**

In the recent time, the demand of complex castings is continuously increasing specially in the field of aerospace, automobile, medical, food industries machinery and machine tool. Investment casting being the most traditional manufacturing process is always the most preferred route for producing complex shape near-net parts. In many complex parts, making the undercuts, channels or passage are the most critical and challenging activity. For such complicated castings, cores are used in preparing the investment molds. In practice, sand core, soluble wax core, urea core, salt core, and ceramic material-based cores are typically used in foundry industry. Among these ceramic gives the best properties compared to any other core materials. Currently varieties of ceramic cores are used in investment casting for different metal and alloys. The properties of final cast part significantly affect by the properties of ceramic core, which directly depends on the various core-composition. Many researchers have made and tested cores with various ceramic compositions; however no published research was found which summarizes them in scientifically. This paper presents a study on various ceramic compositions being used in Investment Casting. The article will be helpful for foundry men in selecting the appropriate composition of ceramic core material based on the part specific requirements.



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# INTRODUCTION

Investment casting is a process to make the casting into single piece ceramic shell moulds, without parting line with high degree of dimensional accuracy and high surface quality. In recent time, the investment casting producers are frequently produced the complex hollow shape like passages, channels, undercuts, bent pipes etc. in cast components without lowering the properties. Such hollow shapes are formed by positioning a required configured core in the investment casting mold. In practice, core is fabricated using sand, soluble wax, urea, salt, and ceramic materials based in investment casting. Among, these core materials specially for thin and small sections, ceramic based materials is only suitable because of difficulty arises during shelling. In terms of strength, stability at high temperature, surface finish and dimensional accuracy ceramic material based core shows much better than any core materials. However, to achieve the quality result, the appropriate ceramic compositions to be selected. Many factors are considered to the selection of the core material like size of the core, complexity of the geometry, shrink rate, tooling and materials to be cast. Ceramic core can be used for different types of metal and alloys casting like high melting materials titanium, nickel and cobalt based alloys, steels and aluminum.

The first step in the production of a hollow type of cavity by a typical investment casting process is to place the core in a cavity die and to inject wax or other destructible pattern material around the core. Sprue components including gates, down poles and the like are also injected and, together with the cored patterns of the part desired, are assembled into clusters. Thereafter, the assembly of pattern and core are dipped in ceramic slurry and dried as in U.S. Pat. No. 2,392,864.These steps are repeated many times to produce a required multilayer shell thickness surrounding the pattern. After the desired number of layers have been formed on the shell mold then the mold has been thoroughly dried, the wax is removed by the application of heat. The most commonly methods used for dewaxing are Autoclave and flash firing dewaxing. After removal of the wax pattern from the ceramic shell mold, the position of ceramic cores remains sameso as required openings, channel, cavities or the like in the final shape of casting to be cast. After firing and cleaning, the mold is ready for use in metal casting. A molten metal or alloy is poured into a mold containing a core. After the solidification of metal, the core and shell mold are removed to free the casting with hollow shape. The ceramic core is removed by various means such as chemical process, thermal process, mechanical process or other means. The architecture of the internal shape in the casting is determined by the core features.

**The ceramics core should satisfy the some requirements (Shaw, 1946; Steven):**

- Chemical stability with the molten metal, absence of reactivity, good dimensional stability, low creep, and resistance to high temperature.
- High porosity (>20%) and can be easily leached from the cast piece to avoid undue production cost.
- Having high strength and low shrinkage characteristics, in order to retain the highly precise shape and size of the cast part and good mechanical characteristics.
- Ceramic cores are used extensively in the manufacturing of castvanes and turbine blades of a gas turbine engine, blocks, cylinder heads and many more. Gas turbine engines are widely used in electric power generation, aircraft propulsion and Ship propulsion.

**Core Raw Materials:** There are many factors that consider selecting the core material. The important factor that considered would be the size of the core and the complexity of the geometry, shrink rate and the source of the tooling and the cost considerations of the core. Ceramic cores are made using Silica, alumina, Zircon, Zirconia, chromia, mullite and hafnia or other suitable materials and mixtures. The selection of compositions are taught by US 7,287,573 in the process of conventional core making for investment casting. US 7,413,001, describe the lesser reactivity ceramic compositions in the form of geometrically complex articles.US 2014/0182809 is focused on the use of compositions to closely match the coefficient of thermal expansion of the ceramic material to a refractory metal component. Ceramic core made by different compositions and their properties.

Silica- Silica ($SiO_2$) is a most commonly used core material in investment casting because of its low coefficient of thermal expansion, high-temperature dimensional stability, ease of removal from the casting and easily availability.In some instances, some metal or metal alloys react with the conventional silica based ceramic core. Therefore, the use of silica-containing core materials for casting of reactive metals is known to be problematic, as silica may react with certain metals during the casting process. Alumina-The use of silica based cores is limited when precision and definition of the internal passage is needed. The use of alumina based cores is desirable since alumina is more robust and can provide better dimensional tolerances in internal passages and other applications. However, the process used to leach or dissolve alumina based cores is not efficient than silica cores. This is because the leaching rate for alumina cores is longer and time consuming, making it economically unfeasible for production and manufacturing operations. Alumina core compositions of the prior art useful for casting reactive alloys, such as US 4,837,187 and US 5,409,871. US 5,580,837, are known, and consist of alumina and other additives in a thermoplastic organic polymer binder. These binders are solids at room temperature, and should be mixed at elevated temperatures in the molten state. Zircon - Zircon is usually used as a main additive to silica-based ceramic core and alumina based ceramic core materials in order to improve their properties. Zircon, or zirconium silicate ($ZrSiO_4$), has low coefficient of thermal expansion, high thermal stability and chemical stability. Other additives that may be present in the ceramic core are like aluminum, yttrium, hafnium, yttrium aluminate, rare earth aluminates, colloidal alumina, oxides of aluminum, yttrium, hafnium, magnesium, and/or Zirconium for increasing refractory properties of the shell mold or core composition. In addition, dispersants, such as Stearic or oleic acid, may be added. In order to further enhance the leach time the core may be included such as calcium carbonate and/or starch. Binder- The binders used in the core composition are mainly depends on type of moulding method .While binder can be organic compound or inorganic compound materials. Organic binder that used in ceramic core are thermosetting binder material, thermoplastic or cross-linking thermoplastic binder material, and mixtures thereof like gum, wax, ethyl cellulose, polystyrene, polyvinyl acetate, polymerized resin, polyterpene resins, linseed oil, gilsonite, shellac, ethyl silicate etc. Inorganic binder that used in ceramic core are Calcium borate a preferred binder for most core systems although other borates such as magnesium borate could be used as a substitute. Calcium carbonate has been selected as a preferred porogen in the core (also being soluble in mild acid solutions). Other alkaline earth carbonates could be substituted.

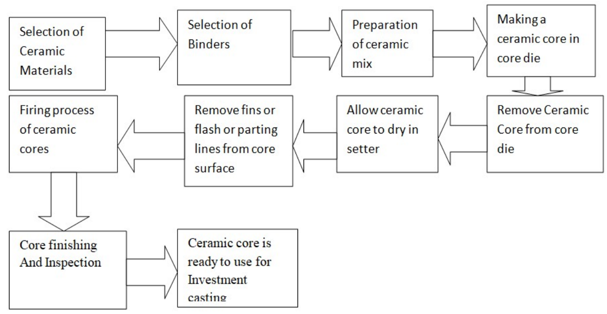


**Figure 1. Ceramic core Making Process**

**Manufacturing method of Ceramic Core:** Various forms of ceramic cores for use in investment casting have been used in the prior casting. Ceramic cores can be preferably made by injection moulding or transfer moulding butit can be formed by other methods also like pouring method, extruded method, form ground method or other conventional methods. The core is extracted from the mould; whatever the method of manufacture it isthen either cured or fired before use. In recent time, additive manufacturing process is also in use for ceramic core making process. Injection moulding method is used specially for making intricate and thin sections. In this process cores are made by injecting slurry (core mix) with pressure into a specially made die and alowed to cure or harden therein to form a green core body.Slurries are prepared by mixing carefully to the ceramic mix and binder, avoiding any excessive turbulence. Temperatures of the slurry (core mix), rate of injection and time of injection are all controlled in the process.The mix materials are injected into the die under controlled conditions. Vacuumcentrifugal equipment has been adopted that allows pressurised centrifugal moulding of slurries in an enclosed vacuum. The cores are then removed from the mould and may be supported on ceramic “slumpers” to protect them from deformation in the “green” state. Controlled and often complex firing cycles are then needed to retain control of shrinkage and dimensional accuracy. U.S. Patent 3,222,435 and U.S. Patent4,737,237 describe injection molding techniques for making ceramic cores for use in casting process.Injection moulding is relatively costly to practice and result in ceramic cores that add considerably to the cost of making the cast metal component. The application of injection moulding cores are like in the production of Formula 1 motor racing cooling systems, oil feeds, turbo inlet ducts, brake ducts, exhausts, side inlets, wing mirrors, fire bottles , turbine components, commercial aerospace, industrial gas turbines, medical and sports equipment (http://www.core-tech-inc.com/ form_ ground.html).


**Figure 1 Different types of ceramic core used in Investment casting (https://core-tech-inc.com)**

**Poured Cores:** Poured (moulded) ceramic cores are produced from a quick setting slurry (core mix). The preparation of ceramic slurry are made by careful mixing of ceramic powders, e.g. ceramic mix and binders. Then, the uniform mixtures of ceramic slurry are poured in the core cavity and after solidification of the core it is removed from the cavity.

| Major component | Minor Component | Casting Materials | Comment |
|---|---|---|---|
| Alumina Flour | Zircon Flour | Aluminium Alloy Binder, Sodium Hydrozen Phosphate, Cane Sugar | [US6,024,787] |
| Fused Silica | Zircon, Zirconia, Aluminia | Nickel and Cobalt Base Super Alloy | Applications-Turbine Blades, Compressor Blades, parts of jet engines and other precious parts [US 7]4,093,01 |
| Silica powder, Alumina Mullite and Zircon | Yuria [Y2O3] | Nickel and Cobalt Base Super Alloy | Ceramic Core are Made by Additive Manufacturing Process [US0306657] |
| Fused Silica | Zircon, Aluminia | Nickel and Cobalt Base Super Alloy | Binder Paraffin Wax and Mineral Wax Plasticizer-bee wax Coupling Agent |
| Silane | | | [US 4989664] |
| Fused Silica | Zircon, Alumina, Cristobalite | Titanium. Zirconium and Super Alloys | Applications-Missile Power Plant, Turbine Drives, Aircraft Engines, and other components of Structural Parts for withstanding extreme high Temperature [ US 4,190,450] |
| Alumina, Yuria | Grain Growth inhibating Agent-MgO, Cr2O3, Carbon Bearing Fugitive Materaial | Super Alloys | Binder- Waz based materials, ethylene vinyl acetate copolymer and Oleic acid [US 4,837,187] |
| | | | |

Then, the solidified (green unfired) core is visually inspected prior to further processing in order that any defective cores can be discarded. The fired ceramic cores are used in a die cavity to inject the wax pattern. Poured cores are used like making in hand rails, handles, catch tanks, water header tanks, hollow reinforcing for hatches, cycle frames and parts, canoe paddles and many others.

Extruded ceramic core- Extruded ceramic core are created by advanced ceramic materials to form ceramic tubes and ceramic rods. These sorts of ceramic core are used for temperature measure instrumentation within the Oil and Gas trade and lots of alternative applications of business heating. They're additionally employed in some specialist part applications. The composition of Extruded ceramic tubes and rods are made up of varied grades of alumina, magnesia, hafnia and silicon dioxide. Such composition offers smart thermal conduction and insulating properties. Extrusion sizes vary from .060 inches to two.500 inches (1.5 to sixty three mm) in diameter with lengths of up to twenty four inches (600 mm).

**Form ground ceramic core:** Form ground ceramic cores are made of extruded shapes that are changed to feature details like a second diameter, tapers, notches, flats, and different routine options. Center less grinding, turning, drilling, and machining are wont to turn out these a lot of complicated shapes. Tolerances on kind ground ceramic cores maintained up to +/- zero.001 inches (0.04 mm) on diameters. Slip Casting Core- In this method ceramic mix poured into a mould made of plaster, plaster absorbers liquid. When, most of the solution has been absorbed and ceramic mix dried then due to shrinkage it easily removed from the mould. After proper inspection, ceramic part left for drying. To remove the volatile binding agent and hardened the core, it is fired at high temperature.

**Additive Manufacturing Process:** In additive manufacturing process, the cores are built in sequential layers, from computer based models, to form a three dimensional object. The computer based model designed by computer aided design (CAD) software. US2015/0306657A1 describes a method of making ceramic core using additive manufacturing process. Some examples of additive manufacturing process are 3D printing, direct deposition, stereo lithography (SLA), selective laser sintering, direct write etc.

**Drying of Core:** Core drying process can be performed by using supporting plates or core carriers or "slumpers". Supporting plates are made of cast aluminium that has been machined to a flat surface. Acore plate may be used in sand core storing and for the baking process. Compositions plates can also be used to carry and bake (5) the cores. These plates are made from suitably heat resisting materials. Batch and continuous type core drying furnaces may be used depending on the kind of core built and production requirements. Portable racks may be used in batch furnaces, for example, drawer types racking in which kind the cores are placed. A large core might take days to dry or a small core might take just a few hours. The drying time is controlled by the rate of travel on the conveyor for continuous type processes. Generally, all core-drying furnaces are air-circulated type, which distribute the heat uniformly. It also carries away the moisture saturated (Jain, 1996) air from the cores. Green ceramic cores can exhibit distortion from stresses induced in the core from themoulding and ambient cooling operations. It can exhibit dimensional variations from one core to the next in a production run of the green ceramic cores.

**Firing Process of Cores:** All ceramic cores may be given a controlled "pre-heat" to reduce the thermal shock of firing that may have a very adverse effect on core properties. The time and amount of firing of the core depend entirely on the composition of the core, the type of binder used and the size of core. The binder changes chemically and molecularly from liquid to solid by oxygen absorption and polymerisation (Greenwood, 1985). Suitable firing is used for the good performance of the core. If a core is heat treated for a small amount of time, it could give off much gas during pouring and solidification. Proper heating of core is done for a long period of time to make hard and brittle it may collapse during solidification. A core heated for a long period may become brittle and collapse under the force of the molten metal or again during solidification. Heating of the ceramic core with the flexible weight bags (Altoonian, 2002) confirms the core to a surface of the "setter" (placing the green ceramic core) to reduce distortion of the core and it improve yields of cores within dimensional tolerances. A ceramic core includes several ceramic layers. Shrinkage rate of the outer surface of the ceramic core layers (Greskovich, 1977) can be easily controlled during firing and it can produce higher density to outer surface of core. The density of the fired ceramic corevaries with the particle size of the materials employed.

**Core finishing And Inspection:** There are number of operations that may be performed on heat-treated cores before they are set in the mould. Core finishing and inspection are required operations adopted to ensure a quality product and to prevent defective cores getting into castings. These may include core cleaning; a dimensional check may be performed. A variety of gauges (measuring devices) may be used in core inspection processes (Uram, 1987) before they are sent to the moulding floor or core storage, e.g. X-ray diffraction, surface finish, dimensional gauge. These type of operations may be performed after the core "pre-heating". If the processes are adopted in the core pre-heating process it may add extra time and cost. The cores should be smooth, free of flash or projections, to be ready for the core setting operation (Mills, 1980).

**Core Assembly:** Some cores are of one piece and may be set directly into the mould after cleaning and sizing. Other cores which are two or more pieces, assembled together before use into the mould. Core assembly can be done mainly by pasting and bolting.

Pastings are used for small cores. The materials used are mixture of talc, dextrin, flour, molasses, water, or other ingredients, is applied to the surfaces to be joined. If pasting does not produce a sufficiently strong assembly then cores may bolt together. For larger core assembly bolting is useful. Bolting are used in manufacturing of gas turbine engines e.g. turbine blade or vane castings.

**Core Setting:** Core setting is the process of placing cores in moulds. The cores must be accurate in size and positioned accurately with respect to the mould cavity. Cores are positioned in the mould by core prints. When metal is poured, cores may rise unless they are securely anchored. Advance planning is required so that the cores will be correctly positioned and firmly held when metal is poured. A number of cores may be assembled and set in the mould at a time.

**Leaching Process for Ceramic Core:** The leaching process for removing cores from metal castings is an important aspect of the overall process for making metal parts. If the core is not completely removed before the part, the residue which remains inside the casting can interfere with the proper performance of the part in service, which sometimes leads to premature failure of the part. To preclude such failures, castings are carefully inspected after leaching to make sure the core is completely removed.

**There are a number of procedures to remove the ceramic cores from the casting, they are by**

- By chemical action
- By application of water
- By thermal stresses ;
- By dynamic action
- By wave action
- By mechanical action

In chemical action on the ceramic core, the strength of the core reduces due to chemical reactions between acting reagents and core materials. Depending on the core compositions, the cores are removed in solutions or melts of alkali, salt and different solutions or melts of solvents and acids. Ceramic cores can be removed in caustic solutions, often under conditions of elevated temperatures and pressures in an autoclave. Fused silica cores may be removed by leaching with molten caustic soda or aqueous hydrofluoric acid (Brown, 2000). The several ceramic cores are developed, which are water soluble or at least disrupt table in water. So that, after the aluminum alloy castings are formed, the ceramic cores can be leached by the use of water (US006024787A) as the alkali solution is not suitable for aluminum alloys castings. The aluminum alloys are subject to chemical attracts by the caustic alkali solution. The ceramic cores can be removed by the dynamic action like jet of water, shot of quartz, abrasive jet with high pressure. In wave action, the various methods for removing the ceramic cores are used. For high strength ceramic core, using ultrasonic is more efficient with the combination of chemical methods (https://core-tech-inc.com).The other action can be used for core removal are like vibration and electric hydraulic.

# CONCLUSION

Ceramic cores give better surface finish and accuracy on casting of complex parts at competitive costs and impressive lead times. Depending on the specific application needed relative to an industrial process, cores can be produced using a wide range of compositions. Additional binders materials and additives can be added to improve the core strength, setting time and other properties. Cores can be manufactured simply and by a process amenable to scale up to commercial levels. Ceramic cores have sufficient refractoriness to withstand molten metal and alloys. Ceramic cores made with a range of compositions can be readily leached using diluted acids or other suitable process.

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