EFFECT OF PROCESS VARIABLES ON THE QUALITY OF CASTING IN INVESTMENT CASTING

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
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MECHANICAL ENGINEERING
(With Specialization in Production & Industrial Systems Engineering)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work carried out in the dissertation entitled, **"EFFECT OF PROCESS VARIABLES ON THE QUALITY OF CASTING IN INVESTMENT CASING"**, is presented on behalf of partial fulfillment of the requirements for the award of degree of "Master of Technology" in Mechanical Engineering with specialization in Production & Industrial Systems Engineering, submitted to the Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee under the supervision of **Dr. D.B. Karunakar**, Assistant Professor, Department of Mechanical and Industrial Engineering.

I have not submitted the record embodied in this report for the award of any other degree or diploma.

Date: 29th June, 2010
Place: Roorkee

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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ABSTRACT

Investment casting is known for its ability to produce components of excellent surface finish, dimensional accuracy and complex shapes. The ceramic shell investment casting process has gained an important position in the family of precision casting techniques owing to the scientific advances in many of its aspects, such as binder solutions, refractory materials, pattern materials, and in the manufacturing process. Yet, the process parameters behind the preparation of wax blends and ceramic slurry make the investment casting process laborious and troublesome. The dimensional changes between the pattern and its corresponding cast part occur as a result of thermal expansion, shrinkage of the pattern material (wax), mould material (shell), and solidifying alloy during processing. The wax blend composition plays an important role to minimize the expansion and shrinkage of pattern and the ceramic slurry composition plays an important role to improve and stabilize the ceramic slurry. In the proposed work, experiments were conducted with different types of waxes namely Paraffin wax, Bees wax, Montan wax and Carnauba wax, varying their proportion. Experiments were also conducted on the ceramic shell by varying the proportions of zircon flour, fused silica, colloidal silica as a binder and catalyst to form the stabilized slurry. The performances of different waxes were studied w.r.t. the shell formation. Using the data obtained from the experiments an attempt was made to find out the set of input parameters, which could offer a set of ideal properties of the wax blend and ceramic slurry. Taguchi method was used to optimize the process parameters. The orthogonal array which represents the matrix of number of parameters that were varied gives the number of tests to be conducted. Taguchi method has successfully suggested the set of input parameters which could offer the desired properties.

Key words: Investment casting, Wax blends, Pattern properties, Ceramic slurry, Slurry properties, Taguchi method.

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CHAPTER 1

INTRODUCTION

1.1 HISTORY

Investment casting has been in practice as early as 4000 B.C. The investment casting technique was largely ignored by modern industry until the dawn of the twentieth century, when it was "rediscovered" by the dental profession for producing crowns and inlays. During World War II, with urgent military demands overtaxing the machine tool industry, the art of investment casting provided a shortcut for producing near-net-shape precision parts and allowed the use of specialized alloys which could not readily be formed by alternative methods.

Investment casting uses a ceramic mould that has been produced by surrounding an expendable pattern with refractory slurry that sets at room temperature. The pattern is then melted out, leaving the mould cavity. Investment casting is also known as the "lost-wax process" or "precision casting".

In sand casting, wood or metal patterns are used to make the impression in the molding material. The pattern can be re-used, but the mould is expendable. In investment casting, a metal pattern die is used to produce the patterns, which are used to produce ceramic moulds. Both the pattern and moulds are expendable. Investment casting is the most flexible of all the precision casting process with respect to precision and the variety of alloys that may be cast within its size limitations. Among the various casting techniques, investment casting is both the newest and the oldest. Among the casting methods in use (precision or conventional), the investment technique is the most flexible. It is competitive with all other casting processes where the size of the products is within a castable range.

Investment castings also compete with powder metal product, forging, stamping, spinning, coined parts, weldments, solderments, brasements and assembled parts held together with rivets, pins, bolts or other fasteners.

Today, Investment Casting is a highly specialized method of producing near net shape. Its advantages are smooth and pleasing finish, reduced machining allowances, close tolerances, flexibility of alloy selection etc. Castings can be made with undercuts, through or blind holes and tapers. The precision investment casting by lost wax process is the most flexible metal forming technique available and also the most cost effective way of designing and manufacturing components for a wide range of manufacturing industry.

The process of the investment casting is suitable for casting a wide range of shapes and contours in small size parts, especially those that are made of hard to machine materials. The process produces excellent surface finish for the casting. In investment casting mould is made in single piece and there is no parting line to leave out fins. This also adds dimensional accuracy to the casting. As from the description of the process, no complication arises when withdrawing a pattern from the mould.

As discussed in the introduction, the ceramic shell investment system was developed to meet the needs of precision, high volume industries. By accurately casting components from a high quality mould, the commercial founder can reduce the amount of skilled machining and finishing undertaken later in the tool shop. For this the moulds used are of two types.

a) Block mould:

In this process metal die is used to produce the pattern. An expendable pattern made up of wax, plastic, tin or frozen mercury is used. The pattern is prepared by attaching suitable gates and risers, and assembly or tree, and is placed inside a container. The slurry of suitable binder plus alumina, silica gypsum, zirconium silicate or mixtures of these and other refractories are then poured into a container surrounding the pattern. The container is vibrated in the whole pouring process to remove air bubbles. After the refractory has taken an initial set, the container is placed in an oven at low heat, the refractory becomes harder and as the temperature of the furnace is raised steadily the pattern either melts and flow from the mould, or volatilizes if made of a plastic such as polystyrene. The mould now contains a cavity in the identical form of the original pattern, the temperature is raised to 600 to 1000°C and molten metal is poured into the hot mould.

b) Shell mould:

In a new technique, refractory costs are minimized by forming only a thin shell of the refractory around the pattern: This is accomplished by dipping the wax assembly into ceramic slurry followed immediately by a coating (stucco) of dry grain. The composition of the slurry and refractory grain is selected primarily based upon the alloys cast. The coated assembly is then allowed to dry in a controlled environment. The dip, stucco and dry are repeated until a shell of sufficient thickness has been formed. After the shell is complete, it is necessary to remove the wax invested within the shell. This is accomplished by either placing the shell into a steam autoclave or directly into a preheated furnace. To minimize shell cracks from wax expansion, it is necessary to reach de-wax temperature in a very few seconds. As the wax melts it exits the shell through the runner or sprue system of the assembly. Prior to casting the shell is fired primarily to develop the fired strength of the ceramic (green or unfired shells have insufficient strength to contain the metal), and then to remove any traces of the wax. After proper firing, the shells are removed from the furnace and immediately cast. The metal enters the shell through the runner or sprue system, which must be of proper design to prevent metallurgical defects due to improper gating.

Die Production

Dies may be made either by machining cavities in two or more matching blocks of steel or by casting a low melting point alloy around a master pattern. For long production runs, steel dies are most satisfactory. The typical dies are as shown in figure 1.1.

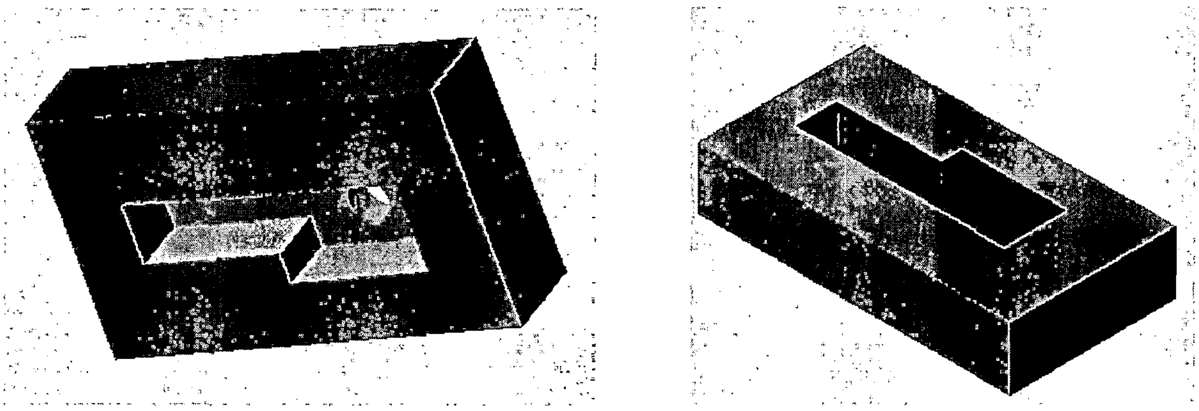


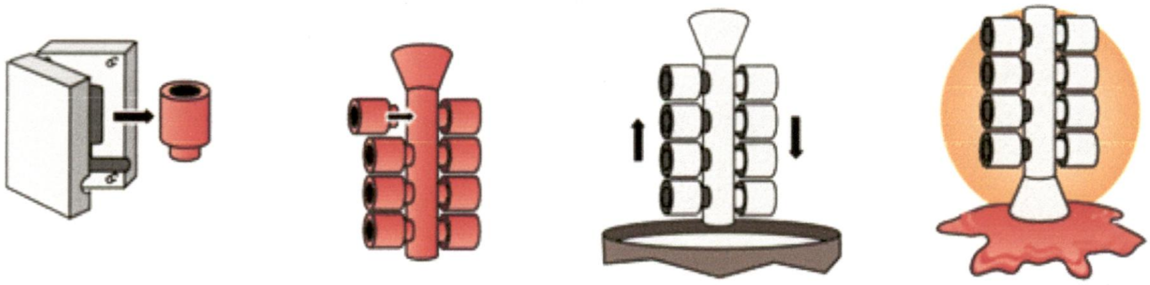
Fig. 1.1: Investment casting dies

1.2 STEPS OF THE INVESTMENT CASTING

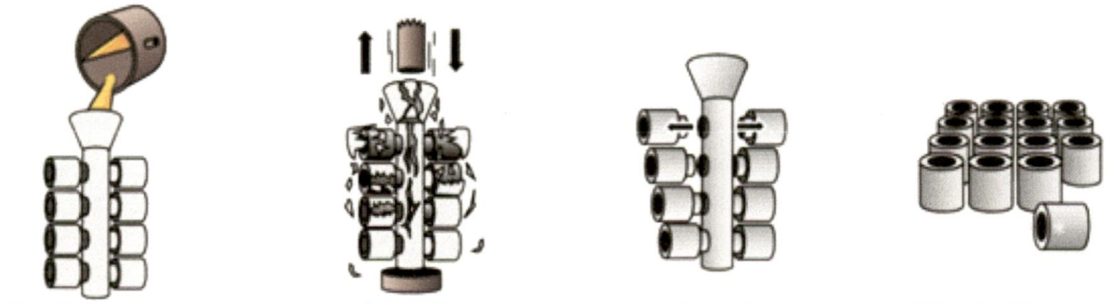
1. Wax injection
2. Assembly
3. Shell building
4. De-waxing
5. Pouring
6. Firing

7. Knockout
8. Cut-off
9. Finishing

The above steps are illustrated in Fig. 1.2.



Wax Injection Assembly Shell Buildiing Dewax/Burnout



Gravity Pouring Knock Out Cut-off Finished Castings

Fig. 1.2: The basic steps in the investment casting process

The above steps can be explained as follows.

1.2.1 Wax injection

An expandable pattern may be made up of plastic, tin, frozen mercury or wax, the wax being most commonly used material. Waxes used are blends of beeswax, carnauba, ceresin, paraffin and other resins. When the wax blend is produced then this blend is injected at 65°C - 75°C into the die using wax injection machine, at a pressure ranging from 7 to 70 kg/cm^3.

The properties desired in a good wax pattern include

1. High tensile strength and hardness so that it can retain its shape while being machined and invested.
2. Good wettability.
3. Resistance to oxidation (This makes the waxes to be reused for many times).

4. Low shrinkage so that the cast products with high accuracy in the dimension can be produced.
5. It should have good adhesiveness (weldability) so that the different sections of pattern can be joined together to form a complex pattern.
6. Solubility in specific solvents.
7. Resistance to chemical action when binders are used in the investment process.
8. It should be chemically resistant to primary cast and to other binders used in the preparation of investment mould.
9. It should be strong and hard in solid state.

1.2.2 Assembly

After the patterns are made individually, these patterns are assembled with a single runner system. Then the wax assembly (wax pattern and running system) is prepared.

1.2.3 Shell building

Ceramic shell investment casting is perhaps the most accurate means of producing a metal casting. The materials used in forming the mould are exceptionally fine and able to reproduce near microscopic detail. Ceramic is also a stable non-reactive material, with minimal expansion and contraction characteristics even when super-heated. A ceramic mould is structurally strong and can withstand both rapid and repeated cycles of heating and cooling. Unlike die casting, a shell mould enables cost effective production of complex, heavily undercut products.

The wax patterns produced are attached to a central wax stick or sprue to form a casting cluster or assembly. The multi-component slurry is prepared, which normally composed of a refractory filler system and a binder system.

The ceramic slurry contains

a) **Binder**

There are two basic binder options for use with ceramic shell investment systems – water based silica sol, or alcohol based ethyl sol. The alcohol version is less common, mainly due to the difficulties of safely maintaining a volatile material. The water based silica sol is normally selected for wetting the first few layers and the more volatile ethyl sol base for secondary 'back up' coats.

b) Slurry refractory

Refractory material is added to the colloid before application to the wax assembly. The added refractory is usually of high quality, finely graded mineral flour. The flour disperses throughout the sol to create the wet refractory material known as ceramic slurry.

The refractory material used to add into the slurry is zircon silicate flour which is the expensive refractory material. The refractory flour is added to the colloidal sol in very precise proportions. The mixture is then stirred continuously to prevent the refractory from separating out from the sol, and settling in a mass at the bottom of the tank.

Once mixed, the slurry is regularly monitored and adjusted to maintain it's optimum quality and consistency. Viscosity is checked using a flow cup, and the slurry's ability to adequately coat the wax pattern is tested by dipping a glass plate into the tank, drying the deposit, then inspecting the glass surface against a strong light source for pin holes and other faults. Ambient room temperatures, humidity within the slurry are also usually monitored.

c) Stucco refractory

As well as the refractory materials and mineral flours present within solution, which combine to form the slurry, a second 'dry' refractory grit is applied separately to the mould when building up the shell's wall thickness. These dry grits are composed of increasingly coarse grades of ceramic. This dry refractory serves function which allows the founder to rapidly build up a wall thickness that is both structurally strong, and semi-porous to evolved casting gases. Ceramic refractory, referred as STUCCO, is made from a dried, fired and processed clay product called fused silica.

d) Other additives

As well as a binder silica/ethyl sol and supplemental refractory zircon silicate/China clay flour/fused silica, wet ceramic slurry requires two further additions to function effectively. First a wetting agent will disperse in the slurry to assist coverage and adhesion to the wax assembly surface. The second additive is an anti-foaming agent which counters the tendency of the wetting agent to produce froth on the slurry's surface. This froth can potentially lead to the transfer of air bubbles to the dipped wax assembly; this in turn would diminish the quality of the cast's surface. Both wetting agent and anti-foam are carefully matched to the manufacturer's colloid.

The following series of steps gives the basic procedures for applying water based ceramic slurry and stucco grits to a wax pattern assembly to build the ceramic shell.

a) Degreasing

The entire wax pattern and assembly is DEGREASED using a proprietary alcohol. Washing also slightly 'etches' the wax. The assembly is drained of any excess alcohol and allowed to air dry. Attention is given ensuring the complete drying out of any interior spaces and deep undercut pockets in the wax trapped alcohol can lead to a poor quality shell and can contaminate and degrade the slurry in the holding tank.

b) First dip

The degreased and dried wax assembly is gradually lowered into the tank containing good grade slurry. The fluid ceramic is carefully worked into the wax pattern's surface and avoiding the entrapment of air. The wax is lifted and held above the tank to drain excess fluid from the assembly.

If a wax assembly is oversize and therefore too large to be tank dipped, the slurry may be poured, brushed or even sprayed over the wax surfaces to apply a coating. Whatever method is used, the aim is to deposit a fine, dense and uniform layer of slurry over the entire wax assembly. The layer should be free of air pockets, runs, finger marks, and any other defects that might transfer to the wax, and later become evident on the surface of the metal cast.

Allow this first deposit to dry before applying a second deposition of slurry, otherwise it may cause the initial layer to lose adhesion with the underlying wax, leading to the deposit's slippage and a poor quality cast surface. To prevent wet slippage and promote rapid drying, one can use the dedicated drying racks. Drying racks allow the assembly to be suspended without damaging the delicate layers of applied investment. This would cause the underlying wax pattern to expand and break up the relatively weak investment wall because of heated air blow.

c) Second dip

Once the first layer of slurry has fully dried, the assembly is re-dipped, again in the first fine grade slurry to ensure any missed areas of wax are fully covered. Then proceed immediately to the next step of stucco application, whilst the dipped assembly is still wet.

d) First stucco application

After the wax assembly has been dipped for a second time and the excess slurry allowed to drain away, the assembly is removed from the tank to a clean area, where a fine powder grade of dry stucco can be dusted over the wetted surfaces. The fine refractory grit is best applied to the dipped assembly either through a graded mesh screen, or by mechanized rain machine. The mesh prevents any oversize particles from penetrating the slurry coating and disturbing the wax. The dry refractory stucco adheres to the wet slurry, with excess stucco falling off the assembly into a collection tray. Once allowed to dry and harden, the slurry and stucco combine to make up the shell's wall. The process is carried out to what extent the ceramic shell thickness is required.

1.2.4 De-waxing

Solid moulds are placed upside down in progressive furnaces. First of all, the Wax pattern is melted and the wax is drained from the mould. As the mould progresses through the furnace, it experiences high temperatures. The oven which melts wax is kept at a temperature of 100 °C to 150 °C.

1.2.5 Firing

Firing of a ceramic shell is one of the most critical steps in the manufacturing process. One must achieve appropriate fired properties at minimum cost and energy consumption to produce the highest quality shells. To get the required results, variables such as temperature, time, firing schedules, and control and particle size distribution should be considered.

1.2.6 Pouring

The metal to be poured is melted in the furnace and brought in small ladles to the preheated moulds for pouring. The moulds are preheated depending upon the metal to be poured e.g. for light alloys and for steels, the preheat temperature should be of the order of 300 ^{0}C to 500 ^{0}C and 800 °C to 1100 °C respectively. Preheated moulds may be filled with molten metal by,

1. Under gravity
2. Under direct air pressure
3. Under centrifugal force.

Molten metal forced into the mould floes properly into sharp details, thin sections and intricate shapes. After they are solidified, the castings are removed from the mould.

1.2.7 Knockout

After the solidification of the metal, the castings are removed from the mould by mechanical vibration or by manually with the hammer by applying low pressure so that the castings will not get damage.

1.2.8 Cut-off

Each casting is separated from the assembly and the gates are removed.

1.2.9 Finishing

After separating the casting from gates finishing of the casting is made. Many inspections are carried out on investment castings. Visual inspections are made for surface faults, gages are employed to check casting dimensions.

Overall, the process of shell building is time consuming because each coat of slurry (each with a corresponding coat of refractory grains) must be air-dried prior to the application of subsequent coats. In the end, the process of dipping, air drying, and redipping requires twenty-four to forty-eight hours or even more to complete.

The benefits of the investment casting process may be summed up by the words accuracy, versatility, and finish. Accuracy and versatility stem from the use of a one piece mould without a joint line or the need for draft angles. These features not only give rise to a component shape that is aesthetic and uniform; they also allow the process to give, on a regular basis, consistent and repetitive close tolerances, intricate contours and competitive cost ratios. Versatility extends to the choice of materials since virtually all alloys can be investment cast.

Investment castings are suited for high technology, high volume orders especially in respect of the aeronautical industry. The petroleum, chemical, electronic, defence and automobile industries are also the large users of castings produced by the process.

1.3 ADVANTAGES, DISADVANTAGES AND APPLICATIONS

❖ Advantages

- Possess excellent details, smoother surfaces, and closer tolerances.
- Freedom of design.
- High production rate.
- Castings do not contain any parting line.
- Intricate shapes can be cast.
- Castings produced are sound and free from defects.
- Machining operations can be eliminated thereby attaining considerable saving in cost.
- Thin sections can be cast with wall thickness 1 to 2 mm and hole diameter of 2 mm.

❖ Disadvantages

- Production of wax patterns, investment moulds etc., makes the process relatively expensive as compared with other casting processes.
- Size limitation of the component part to be cast. Most of the castings produced weigh up to 5 kg.
- The process is relatively slow.

The economic value of this process lies in its ability to produce intricate shapes in various alloys that could probably not be produced at all by any other casting process.

❖ Applications

- To fabricate difficult to machine and difficult to work alloys into highly complex shapes such as hollow turbine blades.
- In dentistry and surgical implants.
- For making jewellery and art castings.
- Milling cutters and other types of tools.
- Jet aircraft engine outlet nozzles.
- In automotive and aircraft industries for producing complex shapes parts.
- Corrosion resistant and wear resistant alloy parts used in diesel engines, textile cutting machines and chemical industry equipment.

CHAPTER 2

LITERATURE REVIEW

As investment casting grows in size and complexity, control of their dimensions becomes increasingly important. During the last few years research has been going on for predicting the final casting dimensions. From the literature, some experimental results have been found on wax blend and shell behaviour.

2.1 WAX PATTERNS

Tascyogylu *et al.* [1] presented a paper which explains that waxes are the complex mixtures of many compounds including natural or synthetic wax, solid fillers and even water. Waxes are mixtures of natural or synthetic hydrocarbons of a wide variety of molecular weights; this is critical to understanding their thermo-physical properties. Wax usually refers to a substance that is a solid at ambient temperature and on being subjected to slightly higher temperatures, becomes low viscosity liquid. The chemical composition of waxes is complex; all of the products have relatively wide molecular weight profiles, with the functionality ranging from products, which contain mainly normal alkanes to those, which are mixtures of hydrocarbons and reactive functional species.

Pattern waxes may be classified into four groups: natural waxes, mineral waxes, synthetic waxes and paraffin waxes. In the early years, wax quality control tests were limited to melting point and ash tests. The tests like penetration, specific gravity, viscosity were included later to determine quality of the wax mixture. Thermal analyses like differential thermal analysis thermo mechanical analysis are also used as a quality control check of wax mixtures. And they determined the shrinkage characteristics of waxes and its influence on the final dimensions of casting.

Sabau *et al.* [2] presented a paper which explains the effect of addition of the additives to the wax. Additives used for making investment casting waxes include a variety of materials such as resins, plastics, fillers, oils and plasticizers. Resins are added to the blend to increase strength. Fillers consist of a fine powder material that is primarily used to improve shrinkage characteristics [3]. The investment casting process involves the making of a disposable wax pattern by injecting the wax into a metal mold. After their injection, wax patterns shrink in the dies due to thermal contraction during solidification and subsequent cooling at the end of the dwell time. They determined that when patterns are removed from dies even though they are only partially solid, and continue to shrink after their removal from the die as they cool down. Dimensional changes between the pattern tooling and its corresponding cast part occur as a result of thermal expansion, shrinkage, hot deformation of the pattern material (wax), mould material (shell), and solidifying alloy during the processing. They concluded that understanding of wax pattern deformation is very important in predicting tooling allowances.

Okhuysen *et al.* [4] indicated that shrinkage of the wax is one of the largest components of the overall dimensional changes between the pattern tooling and its corresponding cast part. In order to predict wax tooling allowances, all the factors that determine dimensional changes associated with wax processing must be evaluated. One of the main difficulties in using computer models for the prediction of wax dimensions is the lack of constitutive equations and material properties of the wax.

Gebelin *et al.* [5] The accuracy of the wax patterns used in the investment casting process has a direct bearing on the accuracy achievable in the final cast part. It is usual for the investment caster to use precision-machined metal dies for producing wax patterns when large numbers of highly accurate components are required. A die of this kind can be costly, and there is usually a considerable lead time associated with its production. In deciding the dimensions of the die cavity to be machined, there are two main shrinkage allowances to be considered: the die-to-wax shrinkage and the casting solidification shrinkage. If these allowances are not correct and the final cast part tolerances are not met, then extra cost and time are incurred because the tooling must be reworked. It is, therefore, very important to ensure that all the appropriate factors are considered when applying the shrinkage allowances [6].

Bonilla and Singh *et al.* [7, 8] made some investigations which explain that the injection parameters play an important role in the accuracy of the wax patterns. These parameters include: the injection flowrate; the injection cycle time; the injection temperature; the injection pressure; and the die temperature. It is reported that contraction decreases when cycle time and/or the injection pressure are increased. Injection flowrate appears to have a smaller effect on wax pattern dimensions. Okhuysen *et al.* [4] reported the results of a survey of 18 investment casting companies to determine the tooling allowance practices. It appears that there is no consistency in the way investment casters decide on the application of their tooling shrinkage allowances, nor are there any guidelines available to the industry in deciding appropriate values of such allowances. They found great variations in the tooling allowances used from one investment casting company to another ranging from 1.2% to 3.8% even though all results were collected for casting the same alloys. They used correction factors for different pattern materials. Based on the observations, they found that for an injection temperature of around 61°C, a final linear contraction value around 1.4% is usually reached. They concluded that because of the bulkiness of the component and relatively short cycle times used, a proportion of the mass of the pattern remained at a temperature close to injection temperature even at eject time.

Liu *et al.* [9] presented a paper on new investment casting technology, 'freeze cast process' with ice as pattern. It starts with the building of solid master and silicone mould. The ice patterns are made from the silicone mould by injecting water in the mould and freezing it. There is an advantage of ice pattern in preventing shell cracking during pattern removal. Then ice pattern are made with the mould and dipped in to refrigerated ethyl silicate slurry. After repeating the dipping and drying processes, ceramic shell is made and then it is put in room temperature and allows the ice pattern to melt, drain, and dry.

Liu *et al.* [10] explains that most production wax patterns exhibit an abrupt expansion during de-waxing. In contrast, the ice pattern will shrink, thus relieving the stress on the shell during pattern removal. Because the ice patterns in the FCP process are made from silicone molds, some problems exist, such as multidirectional water expansion during freezing. These problems can be eliminated by making ice patterns with the rapid freeze prototyping (RFP) process. They concluded that the investigation of surface finish of ice pattern is very difficult to measure directly and they used UV urethane to duplicate the surface of an ice pattern and then measured the surface finish of the duplicated urethane part.

Tascroglu *et al.* [11] presented a paper on different additives used in investment casting pattern wax and found that soyaben, which is an environmentally non-hazardous material with low cost, is a novel and superior alternative to the conventional additives in investment casting pattern wax compositions. They demonstrated with their study that by adding soybean flours of different varieties to the wax composition the surface roughness, solidification, shrinkage, viscosity, hardness tensile strength and wettability properties of a sprue wax can be improved to such an extent that it has properties superior to those of a commercial investment casting pattern wax.

Rezavand [12] made an experimental study on dimensional stability of simplified wax models. The dimensional accuracy of wax injection step introduces a great influence on the final dimension and thus on finishing process. The focus of this experimental work was on the injection stage, investigating the effects of processing parameters and the shrinkage of critical dimensions. They had chosen injection temperature and holding time as variable processing parameters. And concluded that, the final dimensions of wax pattern, in the injection step, are affected by: (i) type of wax; (ii) geometry and (iii) process.

Horacek and Lubos [13] studied the influence of injection parameters on the dimensional stability of wax patterns produced by injection molding process. They found an interrelationship between various injection parameters and their dependency on some dimensional parameters. Geometry of the parts was similar to a cross shape.

Yarlagadda and Hock [14] determined the accuracy of wax patterns produced by hard (polyurethane mould) and soft (RTV mold) tooling and optimized the injection parameters used in a low-pressure injection molding.

2.2 CERAMIC SHELL

All ceramic shell moulds are built up from three components; the binder, filler and the stucco materials. Some of the important parameters of an investment casting mould include: green (unfired) strength, fired strength, thermal shock resistance, chemical stability, mould permeability and thermal conductivity. Selection of any refractory filler material for shell making is dependent on a wide variety of factors which can affect the properties of investment slurry, shell and casting and also the economy of the process. Various combinations of materials have been used to produce the ceramic shell mould. These materials are zircon flour which is often used for the first coat while fused silica and alumino-silicates are used for the secondary coats. The binders used are colloidal silica, ethyl silicate, liquid sodium silicate etc.

The properties of the refractory and binder materials used in the ceramic shell mould are as follows.

Zircon flour

Zircon is the mineral zirconium silicate ($ZrSIO_4$). The grains of zircon sands are round in shape and the surface is very smooth and the chemical nature of the material gives it the highest bonding efficiency with organic binder of any sand now available. The average particles size of the available material ranges from AFS GFN 90 to 130 and the grain distribution is quite narrow. Zircon is the only special sand having most of the desirable properties for foundry sand. Its major advantages are:

1. High refractoriness, which increases with increasing alumina content.
2. High mechanical strength at high temperatures.
3. Greater resistance to corrosion.
4. Less reactive toward many alloys.

Aluminum silicate

It is a mixture of 42% to 73 % alumina and remaining silica plus impurities.

Fused silica

The sand which forms the major portion of the moulding sand (up to 96%) is essentially the silica grains. It has been widely used as a refractory for ceramic shell molds, because of low thermal expansion. The sand grains may vary in size from a few micrometers to a few millimeters. Shape of grains may be rounding, sub-angular and angular. The size and shapes of these sand grains greatly affect the properties of the moulding sand.

Binders

The function of the binder is to produce cohesion between the refractory grains in the green or dried state, since bonding materials are not highly refractory. The required strength must be obtained with minimum possible addition. Commonly used binders in investment casting process are:

a) **Ethyl silicate**
b) **Colloidal silica**

Excellent surfaces are obtained with colloidal silica as bonding material. It is manufactured by removing sodium ions form sodium silicate by ion exchange. The product consists of a colloidal dispersion of virtually spherical silica particles in water.

Barnett [15] found that refractory coating plays an important role in the ceramic shell investment casting. It provides refractory protection to ensure no metal penetration and smooth surface of shell mould. Most of the casting surface defects are related to primary coat during the manufacture of an investment casting ceramic shell mould and also due to poor quality in process control. Primary and secondary coat slurries have slightly different requirement for the manufacture of the mould.

Jones and Marquis [16] concluded that the coating materials for ceramic shell investment casting molds fall in three major categories: binders and catalyst, refractory fillers and additives. Each category has specific characteristics and purpose in forming the complete ceramic mold. The binders are of two types: alcohol based and water based. The alcohol based binder is ethyl silicate. Ethyl silicate slurries have relatively short life and must be discarded if they are not used within some definite time. The most commonly used water based binder is colloidal silica which is an aqueous suspension of amorphous silica.

Beeley and Smart [17] found that selection of any refractory filler material for shell making is dependent on a wide variety of factors which can affect the properties of investment slurry, shell and casting and also the economy of the process. The three most commonly used refractory's for ceramic shell molds are zircon, fuse silica, and aluminum silicate, and they are usually used in combination. Various combinations of materials have been used to produce the ceramic mould, but due to its small particle size and chemical inertness with cast alloys, zircon is often used for the first coat while fused silica and alumino-silicates are used for the other shell coats.

McGuire [18] found that fused silica has an extremely low coefficient of thermal expansion and can therefore be used to produce a dimensionally stable ceramic mold. Fused silica is a non-reactive filler and is easier to remove after casting in the knockout and cleanup operations. Fused silica also has good thermal shock resistance and is dimensionally very stable.

Cui and Yang [19] presented a paper which explains that surface finish will be an important characteristic of the casting for that great attention must be given to the nature of the ceramic filler. Stability in handling of the cluster during coating and dewaxing and the specific gas permeability and removal behavior is the demand of ceramic shell investment casting. The main factors determining the surface quality of the ceramic shell mould for investment casting of the metal alloy include the density of the ceramic powder and viscosity of the primary coating slurry.

Liu et al. [20] concluded that proper choice of stucco flours during primary and backup coating is an important aspect of shelling to provide shells consistent porosity, thickness d strength. Zircon sand with an AFS grain fineness range of 100-110 is advisable to use as primary stucco whereas fsed silica or alumino silicate for backup coats similar as the refractory powders. The intermediate stucco usually a -30 +80 mesh is recommended which allows a denser, stronger shell to be built.

Bijvoet [21] found that the actual percentage composition of ceramic shell slurries are usually depends on the particular refractory powder, type and concentration of binder, and desired slurry viscosity. The refractory flour component is the major component by weight (60-80%) of the slurry. Even a good formula will not produce sound casting if the slurry is prepared in the substandard way. In order for slurry to be considered stable it must be well mixed to a point where the viscosity of the slurry is stable. Slurry is considered stable when the viscosity is measured at a less than one second change, when measured at one-hour intervals. The slurries are prepared by adding the refractory powders to the binder liquid. Poorly wet-in slurry will not develop its maximum strength potential and may result in serious shell problems such as shell cracking. [Beeley and Smart][17].

Jones et al. [22] concluded that if the refractory coating slurry is not allowed to drain uniformly, the pattern assembly may have irregular thickness which may affect its strength. Primary coat must have sufficient thickness and porosity to withstand pressure from expanding wax when it is heated during de-waxing. The particle size of the stucco is increased as more coats are add to maintain maximum mould permeability and to provide bulk to the mould. The purpose of the stucco is to present a rough surface, thus facilitating a mechanical bond between the primary coating and the backup coatings.

Hendricks [23] found that the expansion of the wax during heating generate stresses which are sufficiently high enough to crack the green shell. To reduce the tendency for mold cracking, molds are heated very quickly, so that the surface of the pattern melts before the temperature of the main body of pattern rises. As the pattern heats up and expands, the melted surface layer is squeezed out of the mold, making space for the expanding pattern and preventing the mold from cracking. Higher the heat input thinner the wax expansion.

Jones and Yuan [24] found that a weakened ceramic shell structure can lower the quality of an investment casting. The strength of a ceramic shell mould is a function of such factors as: mould material, shell build-up procedure, and firing procedure. The permeability of the ceramic shell mould has an important influence on the mould filling. Mould filling is improved by increasing the permeability of the ceramic shell. The polymer modified binders also reduces the fired strength due to bum out of the organic phase which in turn by increasing the permeability decreases possibility of misrun or non fill of the castings. However, liquid polymer additions relatively expensive and previous work has shown that the green strength of a polymer modified shell is reduced significantly when placed in a steam bath for a relatively short period of time.

Roberts *et al.* [25] showed that by using slurry of seven millimicron sol containing fused silica grains of three different particle sizes the resultant structure was stronger in both the green and fired states. Although the polymer modified system exhibits a higher strength in the green dry stage, in practice, moulds produced with fiber additions are less susceptible to autoclave cracking. It has also been suggested that the dry green strength is not an accurate measure of the shell crack. They also carried out a survey of 11 shell systems and found that least deformation had occurred with silica-sol-bonded fused silica and the worst with ethyl silicate-bonded molochite. According to him the main factors which affected the shell strength were the particle size of the binder, the shape of the refractory grains, and ceramic bond between binder and filler grain. And also compared the steel wire reinforced investment mould with non reinforced specimens and concluded that firing temperature can be reduced by 5% to 10% with reinforcement of invested layers in investment castings without any loss to surface finish of the casting.

Singh *et al.* [26, 27] presented a paper on the study of the effect of primary slurry parameters on the ceramic retention test. They calculated the variations in coating thickness for slurry and ceramic shell moulds made on wax plate using primary slurry and coarse fused-silica sand as stucco. Analysis was done to identify the various phases present in the ceramic slurry coating. The quality of ceramic shells is dependent on the slurry and shell materials as well as the process by which the shells are built.

He reviewed the key requirement of the investment casting shell as

1. Sufficient green (unfired) strength to withstand wax removal without Failure.
2. Sufficient fired strength to withstand the weight of cast metal.
3. High thermal shock resistance to prevent cracking during metal pouring.
4. High chemical stability.
5. Low reactivity with the metals being cast to improve the surface finish.
6. Sufficient mould permeability and thermal conductivity to maintain adequate thermal transfer through the mould wall and hence allow the metal to cool.
7. Low thermal expansion to limit dimensional changes within the mould wall and ultimately the casting.

The goal of any slurry makeup is to produce stable slurry. In order for slurry to be considered stable it must be well mixed to a point where the viscosity of the slurry is stable. They made a study by changing composition of the refractory materials, binders and filler materials.

Yuan *et al.* [28] presented a paper which explains the use of polymer modified mould. The removal of wax from an unfired ceramic shell system without cracking or dimensional alterations is a key stage within the investment casting process. The polymer modified system exhibited a higher mechanical strength in the green dry state, but that strength reduced when subjected to a simulated autoclave condition. As both wax and ceramic will expand during heating and the weak unfired ceramic shell, in presence of steam, is prone to cracking during the process, so, polymer is added to increase the green strength of the ceramic shell. **S. Jones** explains that the green strength of a polymer modified shell is reduced significantly when placed in a steam bath for a relatively short period of time. The polymer can no longer act as a strengthening material when subjected to the high temperature. The use of polymer modified binders reduces fired strength due to burn out of the organic phase. This in turn increases permeability of the ceramic, reducing the incidence of mis-run or non fill of the casting.

Yuan *et al.* [29] presented a paper which explains the fibre modified ceramic shell. Fibre reinforced ceramic has a lower green strength than the polymer modified system. Although the polymer modified system exhibits a higher strength in the green dry stage, in practice, moulds produced with fibre additions are less susceptible to autoclave cracking. The polymer can no longer act as a strengthening material when subjected to the high temperature and the presence of moisture. The adjusted fracture load bearing capacity (AFL) of the fibre system is higher than the polymer when the samples are wet. This explains why in foundry observation, fibre modified shells are stronger and less susceptible to cracking in the autoclave.

Chakrabarti *et al.* [30] presented a paper which explains the use of acetone based polysilicic acid binder which also provides silica bonds between refractory particles and at the same time serves as an alternative to costly ethyl silicate or colloidal silica.

Li *et al.* [31] presented a paper which explains the influence of shell preheat temperature, pouring temperature, and melt hydrogen content on the microporosity and mechanical properties of the cast patterns. They concluded that the shell preheat temperature and hydrogen content are the most important process variables determining the amount of microporosity in the investment casting. The porosity is increased by increasing the shell preheat temperature and hydrogen content. The low pouring temperature generally produces high mechanical properties.

Baumeister *et al.* [32] presented a paper which explains the influence of casting parameters on the microstructure and the mechanical properties of extremely small parts produced by micro-casting. And he concluded that for the specimens edges become sharper with increasing mold temperature. High mold temperatures also result in the transfer of extremely fine details such as cracks and other surface defects from the mold onto the cast part. At a moderate these undesirable fine details are not critical thus making this temperature optimum for casting.

Sabau *et al.* [33] presented a paper which explains that the solidification, heat transfer, stress state, and the deformation behavior of the metal in the semisolid and solid state must be considered in order to predict the final dimensions and the alloy tooling allowances based on a combined analysis of heat transfer and deformation phenomena in the investment casting process. he concluded that accurate predictions were obtained for all measured dimensions when the shell mold was considered a deformable material. The deformation formed is shown in fig. 2.1.

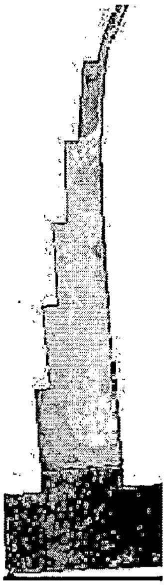


Fig. 2.1: Deformation after casting [33]

Rafique [34] presented a paper in which he explained the heat transfer during solidification and the metal properties obtained after solidification. He explained that dimensional difference between the wax pattern produced and metal part casted occur as a result of solidification and deformation behavior of metal, wax and shell molding materials. The differences between wax pattern and die and between final part and shell are known as shrinkage allowances of wax and metal, respectively. These allowances should be taken into account before the designing of successful investment casting system. Time taken for solidification is one of the most important factors governing the overall quality of casting. The faster the solidification time, better would be strength, and quality of casting and vice versa. And he concluded that heat transfer during solidification is very much dependent upon mold geometry as well as configuration of parts attached to tree. They are also dependent upon mold wall thickness and number of coats.

2.3 SUMARRY OF LITERATURE REVIEW

The overall process of mixing wax blends for pattern making and preparing ceramic slurry for shell building is time consuming. The best wax blend is required to minimize the expansion and shrinkage while heating and cooling respectively. To build the shell, it requires subsequent coats of the slurry and stucco and then air drying which requires 8 hrs to 24 hrs.

Many wax blends are used to test the shrinkage characteristics and its influence on final dimensions of the pattern and casting. The injection parameters play an important role in the accuracy of the wax patterns. These parameters include: the injection flowrate; the injection cycle time; the injection temperature; the injection pressure; and the die temperature.

The ice patterns are made to remove the expansion factor of wax. As the ice pattern will shrink while heating thus relieving the stress on the shell during pattern removal. But the measurement of surface finish of ice pattern is very difficult to measure directly.

The important parameters of an investment casting mould include: green (unfired) strength, fired strength, thermal shock resistance, chemical stability, mould permeability and thermal conductivity. Selection of any refractory filler material for shell making is dependent on a wide variety of factors which can affect the properties of investment slurry, shell and casting. The quality of ceramic shells is dependent on the slurry and shell materials as well as the process by which the shells are built. Even a good slurry formula will not produce sound castings if the slurry is prepared in a substandard way.

The removal of wax from an unfired ceramic shell system without cracking or dimensional alterations is a key stage within the investment casting process.

The polymer modified system exhibited a higher mechanical strength in the green dry state. And reduce strength after firing due to burn out of the organic phase. This in turn increases permeability of the ceramic, reducing the incidence of mis-run or non fill of the casting. But these shells are susceptible to cracking. Though the fibre modified shells have lower green strength but it will not reduce its strength after firing, thus these shells are less susceptible to cracking.

Dimensional difference between the wax pattern produced and metal part casted occur as a result of solidification and deformation behavior of metal, wax and shell molding materials. Time taken for solidification is one of the most important factors governing the overall quality of casting. The faster the solidification time, better would be strength, and quality of casting and vice versa.

2.4 GAP AREAS

1. The study is going on to minimize the shrinkage and expansion of wax blends, but till now no study has the appropriate combination of wax blends which minimizes shrinkage and expansion. By changing the composition of existing wax blends and by using other additives we can determine the above characteristics.
2. The study is going on to prepare ceramic slurry which gives better strength and reduced pattern-to-pour time. By changing the parameters like refractory material, binders, fillers etc. we can increase the life and strength of the ceramic slurry.

2.5 PROPOSED WORK

In the proposed work, the performance of different waxes and wax blends will be studied by varying the proportion of bees wax, paraffin wax, carnauba wax and montan wax. Further, the composition of ceramic slurry will be modified by varying composition of binder, filler and stucco material so as to obtain better surface finish and minimum pattern-to-pour time.

CHAPTER 3

SELECTION OF PROCESS PARAMETERS

In this chapter the selection of process variables, which may affect the casting quality is described. The wax pattern quality characteristic, pattern coating material characteristic and casting quality characteristics were measured. The range of process variables was decided on the basis of literature survey and Taguchi design of experiment is used to conduct the experiments.

3.1 OVERVIEW OF TAGUCHI METHOD

Taguchi's comprehensive system of quality engineering is one of the great engineering achievements of the 20th century. His methods focus on the effective application of engineering strategies rather than advanced statistical techniques.

Taguchi's philosophy is based on the following three simple and fundamental concepts.

a. Quality should be designed into the product and not into the inspection.
b. Quality is the best achieved by minimizing the deviations from the target. The product or process should be so designed that it is immune to uncontrollable environmental variables.
c. The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

At the core of product and process design is the concept of experimental design. In selecting combinations of the various factor levels that enable us to determine the output characteristic and thereby calculate the performance statistic. The matrix that designates the settings of the controllable factors (design parameters) for each run, or experiment, is called inner array by Taguchi; the matrix that designates the setting of the uncontrollable or noise factors is called an outer array. Each run consists of a setting of the design parameters and an associated setting of the noise factors. The inner and outer arrays are respectively designated as the design and noise matrices [35].

3.1.1 Experimental design strategy

Taguchi recommends Orthogonal Array (OA) for laying out of experiments. OA's are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The use of linear graphs and triangular tables suggested by Taguchi makes the assignment of parameters simple. In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives;

- To establish the best or the optimum condition for a product or process
- To estimate the contribution of individual parameters and interactions
- To estimate the response under the optimum condition

The selection of a particular orthogonal array is based on the number of levels of various factors. Here, to conduct the experiments we selected 4 factors and each at 3 levels. Now the Degree of Freedom (DOF) can be calculated by the formula as

$$(DOF)_R = P*(L-1)$$

$(DOF)_R$ = degree's of freedom

P = number of factors

L = number of levels

$$(DOF)_R = 4(3-1) = 8$$

However, total DOF of the orthogonal array (OA) should be greater than or equal to the total DOF required for the experiment. Thus, we selected the L_9 orthogonal array to make the further experiments. This array specifies 9 experiments. The L_9 OA with 4 factors, 3 levels and its responses are shown in the Table 3.1.

Table 3.1: L9 Orthogonal Array

Expt. No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The stages to go through are as follows

- Selection of the factors to be evaluated.
- Selection of number of levels.
- Selection of appropriate orthogonal array.
- Assignment of factors to the columns.
- Conduct the experiment.
- Analyze the results.

3.2 SELECTION OF WAX BLEND PARAMETRS

The accuracy of the wax patterns used in the investment casting process has a direct effect on the accuracy achievable in the final cast part. Production of adequate patterns is of most importance in the investment casting process. Therefore the use of optimum wax proportion which gives minimum shrinkage and surface roughness is of considerable importance. The waxes used and their proportions are given bellow.

3.2.1 Waxes used

a) Bees wax
b) Paraffin wax
c) Carnauba wax
d) Montan wax

a) Bees wax

This wax is a secretion of bees. Its main components are palmitate, palmitoleate, hydroxypalmitate and oleate esters of long chain alcohols (C30-32) (about 70 to 80% of the total weight). One of the properties of bees wax is that, it gives better surface finish.

b) Paraffin wax

Paraffin is a class of aliphatic hydrocarbons characterized by straight or branched carbon chains, generic formula $C\ nH2n+2$. Their physical properties vary with increasing molecular weight from gases to waxy solids. Paraffin waxes are white, translucent, tasteless and odorless solids consisting of a mixture of solid hydrocarbons of high molecular weight. They are soluble in benzene ligroin and warm alcohol. One of the properties of paraffin wax is that, it gives better surface finish.

c) Carnauba wax

This wax (known as "queen of waxes") is secreted by leaves of a Brasilian palm tree (*Copernicia prunifera cerifera*), about 100 g for one tree in a year. It contains mainly fatty esters (80-85%), free alcohols (10-15%), acids (3-6%) and hydrocarbons (1-3%). One of the properties of carnauba wax is that, it gives better dimensional accuracy.

d) Montan wax

This wax is derived by solvent extraction of lignite or brown coal (sub-bituminous coal). The wax component of Montan is a mixture of long chain (C24-C30) esters (62-68 wt %), long-chain acids (22-26 wt %), and long chain alcohols, ketones, and hydrocarbons (7-15 wt %). Montan wax is hard and is most resistant to oxidation. Carbon papers were the largest consumer of crude Montan wax. The highest present part (30%) of Montan wax is used in car polishes. Additional applications are shoe polishes, electrical insulators, and lubricant in plastics and in paper industry. Table 3.2 gives the properties of the waxes used in the present study.

Table 3.2: Properties of the waxes used

Sr. No.	Name of wax	Density (gm/cc)	Melting point (°C)	Volumetric shrinkage (%)	Viscosity (CP)	Remarks
1	Bees wax	0.97	65	4.85	35	Better surface finish
2	Paraffin wax	0.78	64	4.15	32	Better surface finish
3	Carnauba wax	0.99	87	3.20	40	Good dimensional accuracy
4	Montan wax	1.02	82	2.45	38	Good dimensional accuracy

3.2.2 Wax composition

Preparation of wax pattern is the starting point of the investment casting process. An important consideration in selecting wax composition for investment casting pattern is that it must have consistency and dimensional stability. One serious problem of wax material is that it undergoes for large and uneven shrinkage. In the present work an effort has been made towards the improvement of this process by making pattern using a low shrinkage wax blend. The four types of waxes (bees wax, paraffin wax, carnauba wax and montan wax) with their melting temperatures, densities, volumetric shrinkages and viscosities are mentioned in table 3.2. The proportions selected in the formation of the wax blends are given in table 3.3

Table 3.3: Wax blends and their proportions (by % weight)

Blend Sr. No.	Paraffin wax (%)	Bees wax (%)	Montan wax (%)	Carnauba wax (%)
1.	50	30	0	20
2.	50	30	20	0
3.	50	30	10	10
4.	60	20	10	10
5.	70	10	10	10

3.2.3 Pattern based process variables

Patterns are made by injecting the wax into a die. One of the key demands for better tolerances in the investment casting is to calculate and control the shrinkage of pattern material to improve the accuracy of products. Shrinkage characteristics of waxes and its influence on the final dimensions are of great fundamental importance in getting high quality castings, minimizing product cost and scrap. Based on the review of literature the wax composition and injection variables play an important role in the accuracy of the wax patterns. The following process variables were selected to visualize their effect on the dimensional accuracy and surface roughness of the wax patterns;

a) Injection temperature

b) Die temperature

c) Injection force

d) Holding time

The above process variables were selected to visualize their effect on dimensional accuracy, surface finish and shrinkage characteristics of wax patterns produced for investment casting process. From the literature review the ranges were selected for the study are shown in the table. Further these ranges that were divided into the three levels according to the Taguchi method are as shown in the table 3.4.

Table 3.4: Process variables and their range with levels

Factors	Range	Levels		
		L1	L2	L3
Injection temperature (A)	66 °C – 70 °C	66	68	70
Die temperature (B)	44 °C – 48 °C	44	46	48
Injection force (C)	440 N – 540 N	45	50	55
Holding time (D)	9 min – 11 min	9	10	11

3.3 SELECTION OF CERAMIC SHELL PARAMETERS

Selection of shell mould material is of importance to the successful production of high quality cast parts. Shell materials need to be of sufficiently high refractoriness. The shell materials used, their properties and composition are given bellow.

3.3.1 Slurry material

The materials used for preparing the slurry are as follows:

a) Zircon flour

Zircon is the mineral zirconium silicate ($ZrSIO_4$). Zircon is the only special sand having most of the desirable properties for foundry sand. Its major advantages are:

a. High refractoriness, which increases with increasing alumina content.
b. High mechanical strength at high temperatures.
c. Greater resistance to corrosion.
d. Less reactive toward many alloys.

b) Filler

Aluminum silicate is the common filler material used. It is a mixture of 42% to 73 % alumina and remaining silica plus impurities.

Fused silica is another filler material used.

The sand which forms the major portion of the moulding sand is essentially the silica grains. It has been widely used as a refractory for ceramic shell molds, because of low thermal expansion. The sand grains may vary in size from a few micrometers to a few millimeters. Shape of grains may be rounding, sub-angular and angular. The size and shapes of these sand grains greatly affect the properties of the moulding sand.

c) Binder

The function of the binder is to produce cohesion between the refractory grains in the green or dried state, since bonding materials are not highly refractory. The required strength must be obtained with minimum possible addition. Commonly used binder in investment casting process is colloidal silica. Excellent surfaces are obtained with colloidal silica as bonding material. It is manufactured by removing sodium ions form sodium silicate by ion exchange. The product consists of a colloidal dispersion of virtually spherical silica particles in water.

d) Catalyst

The catalysts used are n-octyl alcohol and triton, which act as antifoaming agents.

3.3.2 Slurry based process variables

The coating materials for ceramic shell investment casting moulds fall in three major categories: binders and catalyst, refractory fillers and additives. Each category has specific characteristics and purpose in forming the complete ceramic mold. Refractory coating plays an important role in the ceramic shell investment casting. It provides refractory protection to ensure no metal penetration and smooth surface of shell mould. Selection of any refractory filler material for shell making is dependent on a wide variety of factors which can affect the properties of investment slurry, shell and casting and also the economy of the process. The three most commonly used refractories for ceramic shell molds are zircon, fuse silica, and aluminum silicate, and they are usually used in combination. Various combinations of materials have been used to produce the ceramic mould, but due to its small particle size and chemical inertness with cast alloys, zircon is often used for the first coat while fused silica and alumino-silicates are used for the remaining shell coats.

The following variables were selected for the study to find out viscosity, density of the slurry and surface roughness of the shell produced.

1. Zircon flour content
2. Filler (fused silica) content
3. Binder (colloidal silica) content
4. Catalyst (50% of n-octyl alcohol and 50% of triton) content

The experiments were conducted using colloidal silica as a binder because the shell produced by ethyl silicate has relatively short life as compared to the shell produced by colloidal silica. The range and levels for conducting the experiments were decided on the basis of literature review and are as shown in the table 3.5.

Table 3.5: Range and levels of process variables.

Process variables	Range	levels		
Zircon flour (gm)	150 – 450	150	300	450
Filler material (gm)	100 – 300	100	200	300
Binder ratio (ml)	2 – 3	2	2.5	3
Catalyst (ml)	3 – 5	3	4	5

After preparing the slurry by using the above combinations, were found out the viscosity, density of the slurry produced and surface roughness of the shell produced were found out. After de-waxing the shell was heated up to 350 °C to 400 °C and then the molten metal which was heated up to 725 °C was poured in to the shell and then the surface finish and hardness of the casting was examined.

CHAPTER 4

EXPERIMENTAL WORK

There are three major stages in ceramic shell investment casting process: the production of wax patterns, the production of the ceramic moulds and the production of metal casting. Pattern dies are used to create wax patterns by injecting wax into dies. The wax patterns are used to create a ceramic shell by the application of a series of ceramic coatings, and the alloy is cast into the de-waxed shell mold. Since an expendable pattern without split lines is used, limitations on design complexity are minimized.

4.1 EXPERIMENTAL SETUP

The whole set up is divided into the following parts:

- (i) Pattern die
- (ii) Wax injection machine
  - a) Wax melting unit
  - b) Wax injection unit
  - c) Die clamping unit
- (iii) Slurry mixture and holding tanks
- (iv) De-waxing device

4.1.1 Pattern die

Dies may be made either by machining cavities in two or more matching blocks of steel or by casting a low melting point alloy around a (metal) master pattern. For long production runs, steel dies are most satisfactory. They are machined from the solid blocks by die sinking and are assembled in the tool room. The dies thus formed, achieve the highest standard of accuracy and have considerable longer life. Dies of low melting point alloys are made by casting and require a master pattern or metal replica of the final casting. The master pattern is given an allowance for subsequent contractions of pattern and metal, up to 2%.The master pattern is used to produce two halves of the die or mould by embedding it in plaster or clay and casting one die half at a time by pouring a low melting point alloy such as that of bismuth or lead. Die halves are sent for necessary machining and drilling the gate through which wax is to be injected for preparing expendable patterns. Cast dies are more economical than sunk dies for short production runs. Die dimensions are re-worked by trial-and-error procedures until casting dimensions are reduced within acceptable dimensional tolerances, increasing the cost of the castings.

For sake of simplicity, it was decided to select a die capable of producing only a single pattern weighing approximately 150 gm. The master pattern used in the present study is shown in Figure 4.1. It was used to produce two halves of the die. The master pattern is given an allowance for subsequent contractions of pattern and metal. A11 the surface details have been included in the die itself. Aluminum is used as a die material. For the fabrication of steeped pattern die and sprue, a cavity as per the pattern dimensions is prepared.

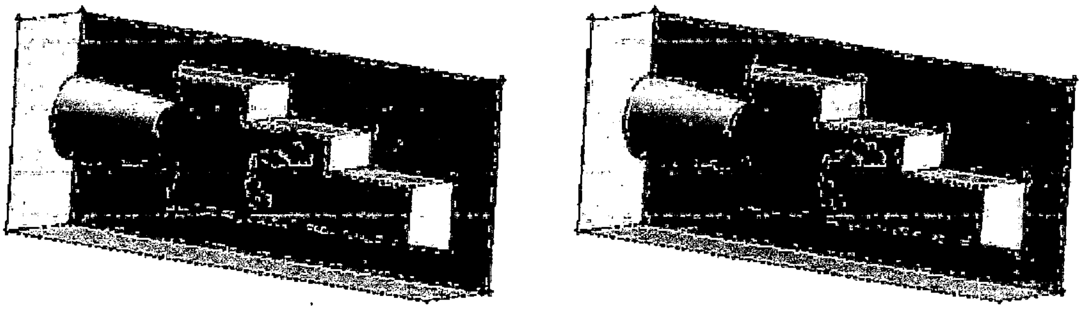


Fig. 4.1: Pattern Die

4.1.2 Wax injection machine

Injection machine is required for the injection of wax into the pattern die. This is of critical importance, since the quality of casting is dictated by the quality of the pattern. Wax injection machine is a machine that takes a preconditioned wax and injects it into a die to produce a wax pattern. Injection machines are classified by the state of the wax that the machine is capable of injecting. Plunger type liquid injection machine is developed and used in the present research work. Equipments of the wax injection unit are shown in Figure 4.2. The tank has a stirrer, thermostat, hand valve, and nozzle. This machine is usually limited to pressure less than 650 kPa and only injects liquid wax for large variety of small parts. The injection machine (Figure 4.4) which was fabricated for the present work, has three basic components; the heating unit, injection unit, and the die clamping system. This machine performs following essential functions;

1. Jacketed heating and melting of the wax in the aluminum reservoir tank along with slow speed stirring.
2. Injecting liquid wax from the brass cylinder under pressure into a closed mold.
3. Maintaining the injected wax under pressure for a specified time to prevent back flow of liquid wax and to compensate for the decrease in volume of melt during solidification.

The above three functions are the operations in which the mechanical and thermal inputs of the injection equipment must be coordinated with the fundamental properties and behavior of the wax being processed.

Other important operations in the injection process include feeding the brass cylinder from an aluminum reservoir gravimetrically through control valve and controlling temperature with thermostat during melting, conditioning and injection to ensure high pattern quality. The wax injection temperature control used in the set up is achieved by controlling the temperature in the wax reservoir and in the nozzle. The in-line/horizontal injection system allows the wax to be injected in a straight line from the injection cylinder through nozzle and into the die. This ensures a smooth laminar flow that prevents turbulence in the metallic die.

a) Wax melting unit

It consists of a thin (20 gauge) tapered wall aluminum container. The container is surrounded by asbestos sheet wrapped with electric heating element of nichrome wire and of 1500 watts rating to ensure indirect heating of wax and avoid overheating/oxidation. A wax valve directs molten wax to a nozzle. The heat exchanger then quickly heats the wax to its injection temperature immediately prior to injection. A temperature sensor measures injection temperature. A stirrer is fitted to the centre of top cover plate and is extended to the bottom of the reservoir without touching its surface.

b) Wax injection unit

The cylinder is fitted with nozzle on front side and closed with rubber seal on its back side, while plunger remains inside the cylinder. A valve couples the cylinder to a wax reservoir for injection. One die can be loaded at a time to the wax injection unit.

c) Die clamping unit

The function of clamping unit is to load and unload the die into the injection nozzle. When wax is injected into the die, the pressure tends to force apart the two die halves. To prevent this, the die is clamped. The hand clamping, using bolts is employed for clamping die. The die is placed on the base plate and held in front of the nozzle. Then it is clamped from top and back side using bolts to secure and uniformly compress the two halves of the die which must be removed for disassembly.

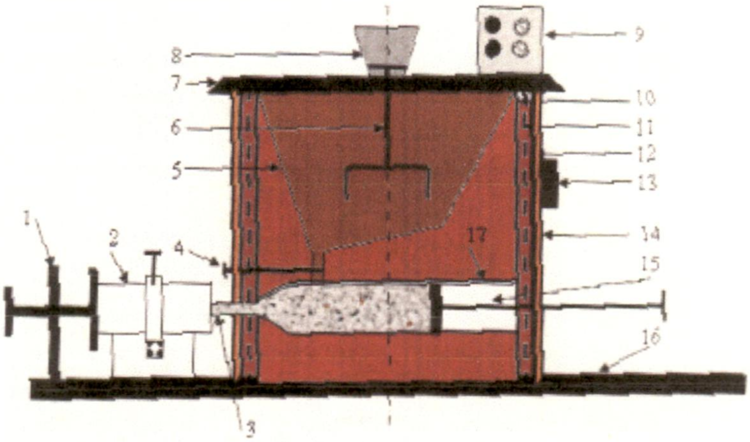


Fig 4.2: Wax injection machine

1) Die clamp, 2) Die, 3) Nozzle, 4) Control valve, 5) Wax reservoir, 6) Stirrer, 7) Cover plate, 8) Electric motor, 9) Temperature controller, 10) Asbestos sheet, 11) Heating coil, 12) Glass wool, 13) Power supply, 14) MS sheet, 15) cylinder and plunger, 16) Base plate.

4.1.3 Slurry mixer and holding tanks

The main objective of slurry mixer is to thoroughly mix the refractory filler and binder to produce stable viscosity of the slurry for a given set of parameters. The requirement of the primary slurry is its ability to flow, coat and adhere to the fine details of wax pattern. A moderate shear propeller type slurry mixer is used with speed controller which provides adequate shearing action to break up the mixture and strips the air off particles from surfaces allowing the slurry to stabilize in a few hours.

4.1.4 De-waxing device

The primary objective of de-waxing system is to remove the wax from the shell without cracking it. The second main objective is to drain out the melted wax out of the oven without burning or decomposing. Successful de-waxing depends on sound design of equipment for applying sufficient heat to the exterior of the ceramic shell so that a thin skin of wax adjacent to the primary coat melts before the bulk of the wax can expand and exert enough pressure to crack the shell. The de-waxing device is as shown in figure 4.3.

Fig 4.3: De-waxing device

4.2 EXPERIMENTAL WORK FOR WAX BLEND

4.2.1 Mixing of wax blends

Four types of waxes (paraffin wax, bees wax, montan wax and carnauba wax) with different melting temperature in between 58 ^{0}C and 89 ^{0}C are selected for the present study. Each wax is in solid state at room temperature. Properties of these waxes are already given in the table 3.2.

The appropriate proportions of these waxes are mixed to obtain the best wax blend. The proportions of these waxes are already shown in the table 3.3.

These waxes are melted to 100 ^{0}C and then mixed in the wax injection machine. The stirrer is used to mix the liquid wax thoroughly.

4.2.2 Wax blend injection

As the wax is melted to 100 ^{0}C and stirred to mix thoroughly, the liquid wax is cooled to required injection temperature. The temperature required is measured with the help of thermometer. The melted wax comes in the cylinder, where with the help of plunger we can inject the molten wax into the die as shown in figure 4.4. The die is heated up to 48 ^{0}C before injecting the wax and the wax injection temperature is maintained up to 70 ^{0}C.

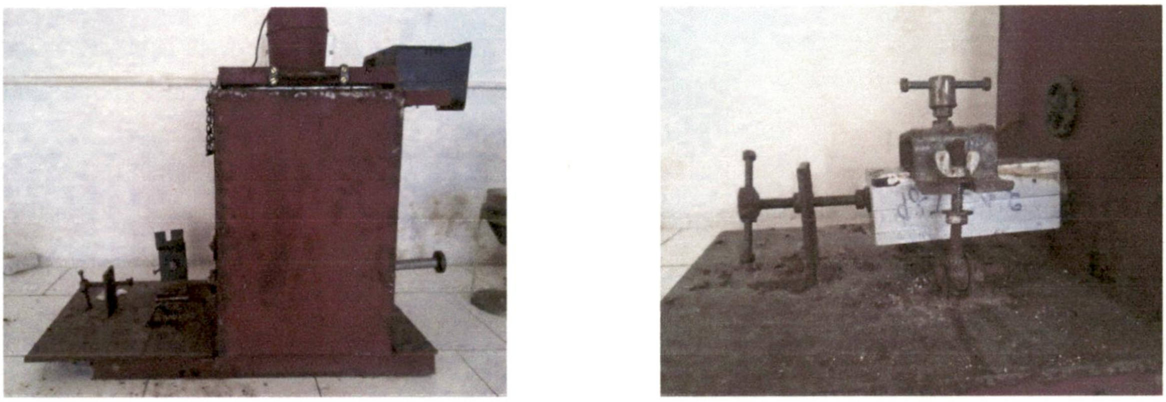


Fig 4.4: Wax blend injection

4.2.3 Withdrawal of pattern

As injected wax enters the die, die temperature increase further. The time required to withdraw the solidified wax pattern from the die is near about 45 min to 1 hour. The wax pattern removed from die is as shown in figure 4.5. If the pattern is removed before this time there are chances of breakdown of the pattern in the two separate halves of the die. The parameters customarily controlled include wax temperature, injection temperature.

Fig 4.5: Withdrawal of pattern from die

4.2.4 Measurement of properties

After the pattern production the following properties are measured.

1) Linear shrinkage
2) Volumetric shrinkage
3) Surface roughness

The following values of injection parameters are used for pattern production:

Injection temperature 65 ^{0}C - 75 ^{0}C

Die temperature 42 ^{0}C – 48 ^{0}C

Injection force up to 600 N

Holding time 9 min – 11min

Solidification time of wax in to dies varies from half to one hour. The dimensions of pattern are calculated to compensate for the several size adjustments, which take place in the process. The average shrinkage of pattern dimensions is calculated from the measured data.

1) Linear shrinkage

Linear shrinkage canbe calculated by measuring the die dimensions and pattern dimensions produced by taking the difference in the dimensions.

2) Volumetric shrinkage

The Volumetric shrinkage is calculated as follows

a) Apply a coating of grease on two halves of die to make it leak-proof from water and align the two-halves of die together.
b) Fill the die cavity with water and measure the volume filled with the help of measuring flask. (V_D)
c) Fill water in a measuring flask and note the initial reading. (V_i)
d) Place the wax patterns made inside the measuring flask, volume rises and take the final reading. (V_f)
e) The difference between the two readings gives the amount of volumetric contraction.
f) The percentage of volumetric contraction given by

$$V_D - (V_f - V_i) / V_D \times 100$$

3) Surface roughness

Surface roughness of the each pattern is measured by using Optical Profiling System device which is of the type Veeco WYKO NTI 100 as shown in figure 4.6.

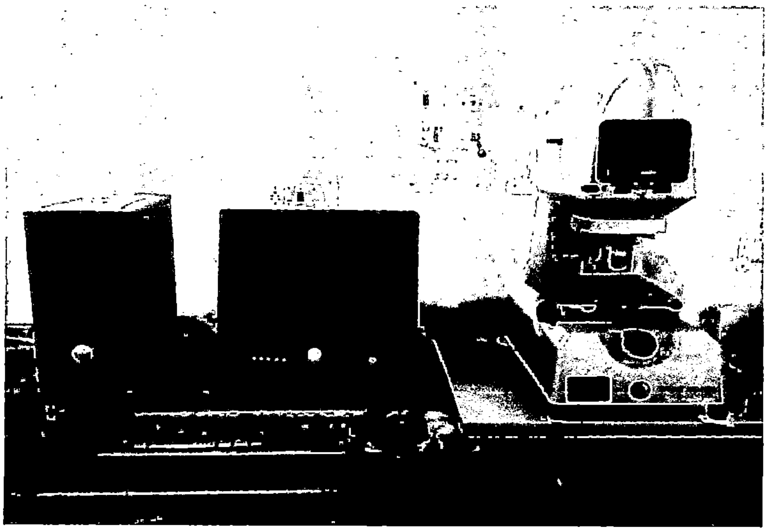


Fig 4.6: Optical profile meter

The Orthogonal Array used to produce the patterns is as shown in the table 4.1.

Table 4.1: L9 Orthogonal Array.

Expt. No.	Process variables			
	Injection Temperature (°C)	Die Temperature (°C)	Injection Force (N)	Holding Time (min)
1	66	44	440	9
2	66	46	490	10
3	66	48	540	11
4	68	44	490	11
5	68	46	540	9
6	68	48	440	10
7	70	44	540	10
8	70	46	440	11
9	70	48	490	9

The pattern dimensions obtained from the different wax blends are listed in the following tables from 4.2 to 4.6. Where in Pij, i= wax blend number and j= pattern number

Table 4.2: Pattern dimensions obtained from Blend 1

Dimension	A	B	C	D	E	F	G	H	I
Die dimensions	96.78	30.80	30.66	35.32	38.59	28.15	19.4	34.4	34.40
P11	95.95	30.42	30.33	35.20	38.46	28.01	19.28	34.17	34.26
P12	95.98	30.56	30.38	35.05	38.39	28.06	19.21	34.23	34.21
P13	96.03	30.45	30.42	35.18	38.51	27.98	19.25	34.28	34.19
P14	96.11	30.57	30.28	35.27	38.49	27.85	19.18	34.19	34.28
P15	96.05	30.60	30.24	35.22	38.31	27.99	19.31	34.11	34.15
P16	96.11	30.49	30.40	35.22	38.50	28.01	19.26	34.26	34.22
P17	96.10	30.50	30.38	35.22	38.47	27.99	19.25	34.25	34.24
P18	96.03	30.47	30.36	35.20	38.49	27.98	19.21	34.23	34.21
P19	96.02	30.42	30.43	35.17	38.51	28.03	19.19	34.21	34.23

Table 4.3: Pattern dimensions obtained from Blend 2

Dimension	A	B	C	D	E	F	G	H	I
Die dimensions	96.78	30.80	30.66	35.32	38.59	28.15	19.4	34.4	34.40
P21	96.40	30.54	30.60	35.27	38.47	28.11	19.35	34.33	34.36
P22	96.46	30.69	30.51	35.25	38.38	28.13	19.36	34.38	34.33
P23	96.34	30.59	30.49	35.26	38.49	28.09	19.38	34.35	34.38
P24	96.36	30.61	30.53	35.24	38.51	28.10	19.38	34.29	34.36
P25	96.46	30.72	30.48	35.28	38.43	28.08	19.31	34.31	34.35
P26	96.45	30.55	30.62	35.28	38.46	28.12	19.34	34.32	34.35
P27	96.46	30.60	30.59	35.27	38.49	28.10	19.35	34.33	34.34
P28	96.44	30.59	30.60	35.25	38.50	28.09	19.32	34.31	34.33
P29	96.47	30.61	30.58	35.28	38.52	28.11	19.30	34.32	34.31

Table 4.4: Pattern dimensions obtained from Blend 3

Dimension	A	B	C	D	E	F	G	H	I
Die dimensions	96.78	30.80	30.66	35.32	38.59	28.15	19.4	34.40	34.40
P31	96.34	30.60	30.50	35.24	38.40	27.91	19.21	34.18	34.14
P32	95.88	30.35	30.36	35.17	38.18	27.91	19.23	34.17	34.18
P33	95.79	30.43	30.31	35.05	38.14	27.88	19.12	34.18	34.19
P34	95.75	30.41	30.26	35.08	38.15	27.90	19.15	34.16	34.22
P35	95.73	30.39	30.27	35.07	38.11	27.83	19.10	34.15	34.16
P36	95.86	30.37	30.34	35.15	38.20	27.89	19.26	34.20	34.15
P37	95.82	30.39	30.32	35.18	38.19	27.86	19.25	34.21	34.17
P38	95.76	30.36	30.29	35.11	38.19	27.93	19.17	34.17	34.20
P39	95.79	30.32	30.33	35.14	38.16	27.95	19.21	34.19	34.16

Table 4.5: Pattern dimensions obtained from Blend 4

Dimension	A	B	C	D	E	F	G	H	I
Die dimensions	96.78	30.80	30.66	35.32	38.59	28.15	19.40	34.40	34.40
P41	96.26	30.58	30.47	35.21	38.47	28.08	19.28	34.27	34.29
P42	96.29	30.55	30.50	35.24	38.45	28.05	19.26	34.25	34.27
P43	96.31	30.55	30.51	35.25	38.40	27.98	19.26	34.23	34.25
P44	96.27	30.54	30.49	35.24	38.44	28.03	19.27	34.26	34.27
P45	96.34	30.61	30.52	35.21	38.45	28.06	19.23	34.24	34.25
P46	96.27	30.59	30.46	35.19	38.41	27.99	19.25	34.25	34.28
P47	96.36	30.58	30.52	35.26	38.41	28.09	19.24	34.21	34.24
P48	96.25	30.54	30.48	35.23	38.44	28.05	19.21	34.24	34.21
P49	96.29	30.56	30.47	35.26	38.41	28.01	19.24	34.21	34.23

Table 4.6: Pattern dimensions obtained from Blend 5

Dimension	A	B	C	D	E	F	G	H	I
Die dimensions	96.78	30.80	30.66	35.32	38.59	28.15	19.40	34.40	34.40
P51	95.93	30.39	30.36	35.18	38.19	27.90	19.28	34.21	34.17
P52	96.05	30.46	30.38	35.21	38.43	27.95	19.31	34.23	34.21
P53	96.22	30.50	30.46	35.26	38.31	27.97	19.30	34.18	34.21
P54	96.02	30.42	30.43	35.17	38.51	28.03	19.20	34.21	34.23
P55	96.10	30.55	30.28	35.27	38.49	27.85	19.18	34.19	34.28
P56	96.28	30.62	30.42	35.24	38.40	27.89	19.24	34.16	34.19
P57	95.94	30.41	30.33	35.20	38.46	28.01	19.28	34.17	34.26
P58	96.34	30.61	30.50	35.23	38.41	27.91	19.21	34.18	34.14
P59	96.31	30.59	30.47	35.25	38.37	27.90	19.20	34.20	34.17

The properties calculated from the above five blend are listed in the next chapter.

4.3 EXPERIMENTAL WORK FOR CERMIC SHELL

4.3.1 Preparation of slurry

Shell materials need to be of sufficiently high refractoriness. As a general practice, high refractory facecoat slurry is normally applied to the wax pattern to improve refractoriness. Shells must have sufficient high temperature mechanical stability to ensure dimensional accuracy of cast parts as well. Therefore, shells should neither densify nor creep throughout the process. Much of observed defects in a cast part are actually a result of faulty shell mold production.

These slurries are composed of a refractory system and a binder system. Facecoat layer(s) are constructed through dip coating. Shell mould is constructed by applying multiple dip coatings, around the facecoat layers and stuccoing. Each coat of slurry and refractory grains is air-dried before subsequent coats are applied. Investment mix consists of graded suspension of refractory grains in suitable media with binders. For preparation of slurry, the ingredients are accurately weighed. The mixture is then stirred for few minutes, covered and left for aging for approximately 18 hours. At the end of aging period, measured quantity of filler is added slowly to slurry followed by stirring. Mixture is then stirred by an impeller run by motor in a mixer for approximately 72 hours as shown in figure 4.7. Other additives are added and slurry becomes ready for dip coating. Slurry compositions are usually proprietary; the actual percentage composition of ceramic shell slurries depends on the particular refractory powder, type and concentration of binder, desired slurry viscosity, density.

Fig 4.7: Slurry preparation

4.3.2 Coating of wax patterns

The wax pattern assembly is dipped into slurry of a refractory coating material. A number of patterns (depending on size and complexity) are attached to a central wax stick, or sprue, to form a casting cluster, or assembly. A wax pattern assembly is then dipped into the primary slurry. The ceramic coating is built through successive stages of dipping and stuccoing. The purpose of the stuccoing is to minimize drying stresses in the coatings. This procedure is repeated until the required shell thickness is obtained. Thickness of the shell depends on the details of the process but is generally of the order of 6 mm to 15 mm. The ceramic coating is allowed to dry before it goes for the next dip. Enough layers must be applied to build a shell strong enough to withstand subsequent operations. The shells built are shown in figure 4.8. On completion of the coating and after the shell is completely dry, the wax pattern is melted out in a high pressure steam autoclave, leaving a hollow void within the mold, which exactly matches the shape of the assembly. Prior to casting, the shells are fired in an oven where intense heat burns out any remaining wax residue and prepares the mold for the molten metal. After the molten metal is poured and solidified, the shell is broken away and finally gates and risers are cut off.

Fig 4.8: Coating of wax patterns

The secondary slurry used is of kynite flour and fused silica with proportions of 300 gm and 200 gm respectively. The 120 mesh zircon sand is used as primary stucco and 30/80 mesh calcinited coat sand up to 2 to 3 layer and 16/80 mesh calcinited coat sand up to 3 layers are used as secondary stucco respectively. The drainage time is of 90 seconds to drain out the excess slurry from the surface and setting time is 5 to 10 minutes to set the first coat.

4.3.3 De-waxing and firing of mould

Solid moulds are placed upside down in furnaces. First of all, the wax pattern is melted and the wax is drained from the mould. The oven which melts wax is kept at a temperature of 100 °C to 150 °C.

After removing the wax, the shell can be quickly fired at a desired temperature. Firing of mould brings full development of dry strength, eliminates traces of organic material and preheats the mould to casting temperature, thus facilitating metal flow and reproduction of mould details.

4.3.4 Melting and pouring of metal

The metal to be pour is melted in an induction furnace and brought in a small ladle to preheated moulds for pouring. The figure 4.9 shows the shell after pouring the molten metal. Moulds are preheated (before getting poured) to about 1100 ^{0}C depending upon the metal to be poured e.g., for light alloys and for steels, the preheated mould temperatures should be of the order of 300 ^{0}C to 500 ^{0}C and 800 ^{0}C to 1100 ^{0}C respectively. For preparing casting of non-ferrous alloy, Al-7% Si alloy was selected because of its good castability characteristics. Silicon is good in metallic alloys used for casting. This is because it increases the fluidity of the melt, reduces the melting temperature, decreases the contraction associated with solidification and is very cheap as a raw material.

Fig 4.9: Pouring of metal

4.3.5 Evaluation of ceramic slurry and casting quality

a) Slurry viscosity

Viscosity was calculated using the Brookfield viscometer (accuracy: ± 1.0% of range, reproducibility: ± .2%, speed: 0.01 to 200 rpm). All the values are measures at constant speed.

b) Slurry density

Density of slurry is determined with the use of conventional method by measuring mass and volume.

c) Dimensional accuracy measurement

Dimensional accuracy is measured with the help of Digital Vernier caliper having least count of 0.01mm.

d) Surface roughness measurement

Surface roughness of the each pattern is measured by using Optical Profiling System device which is of the type Veeco WYKO NTI 100.

e) Hardness measurement

The Brinell Hardness Number (BHN) of the test specimens were measured on DIA TRONIC 2 Hardness Testing Machine at a load of 62.5 kg using ball of diameter 5mm and indentation was measured on the evenly polished surface of test specimen. The hardness numbers were noted from the tables, which gives values of hardness numbers for different diameter of impression of indentation at different ratios of load to square of ball diameter.

The Orthogonal Array used to prepare the different types of slurry is as shown in the table 4.7. The properties calculated of the different slurries prepared are listed in the next chapter.

Table 4.7: L9 Orthogonal Array

Expt. No.	Process variables			
	Zircon flour (gm)	Filler (gm)	Binder ratio	Catalyst (ml)
1	150	100	2	3
2	150	200	2.5	4
3	150	300	3	5
4	300	100	2.5	5
5	300	200	3	3
6	300	300	2	4
7	450	100	3	4
8	450	200	2	5
9	450	300	2.5	3

CHAPTER 5

RESULTS AND DISCUSSION

If the conventional method is used to carry out the experiments then for selected process parameter we have to conduct the experiment for their selected ranges. Likewise the experiments are more and time consuming. So, it better to use the technique which reduces the number of experiments to be carried out and optimizes the process parameters. Taguchi method is used for optimization. Here the numbers of experiments to be carried out are 9. The software used to carry out the Taguchi experimental analysis is MINITAB solutions.

5.1 STANDARDIZATION OF WAX PROPORTION

The wax pattern deformation is very important in predicting tooling allowances. Shrinkage of the wax is one of the largest components of the overall dimensional change between the pattern tooling and its corresponding cast part. In order to predict wax tooling allowances, all the factors that determine dimensional changes associated with wax processing must be evaluated. The average linear shrinkage of pattern dimensions, volumetric shrinkage and surface roughness are calculated from the measured data. It was observed during the investigations that considerable variations took place in the dimensions of the patterns and it was necessary to control these variations in order to produce them within close tolerances. The result indicates that the phase change of the pattern from the liquid to solid state is accompanied by volume contraction. The average properties of the wax blends are as shown in table 5.1.

Table 5.1: Wax blend properties value

Blend No.	Average linear shrinkage (%)	Average Volumetric shrinkage(%)	Average surface roughness (μm)
1	1.70	5.12	1.43
2	0.723	2.56	0.766
3	2.49	9.52	1.71
4	1.36	4.47	1.22
5	1.75	5.27	1.23

The results obtained by using the Taguchi design of experiments are summarized in the table 5.2. After conducting the experiments it is observed that wax blend 2 gives minimum shrinkage and surface roughness as shown in the graphs (Figure 5.1 to Figure 5.3).

Table 5.2: Experimental data of Wax Blends

Expt. No.	Process variables				Measured properties														
	A	B	C	D	Blend 1			Blend 2			Blend 3			Blend 4			Blend 5		
					%LS	%VS	S.R	%LS	%VS	S.R	%LS	%VS	S.R	%LS	%VS	S.R	%LS	%VS	S.R
1	66	44	440	9	1.73	5.10	1.23	0.74	2.79	1.09	1.79	9.17	1.59	1.19	4.36	1.09	1.71	5.14	1.01
2	66	46	490	10	1.87	5.18	1.33	0.71	2.56	0.75	2.41	8.83	1.80	1.28	4.53	1.20	1.69	5.29	1.19
3	66	48	540	11	1.59	5.09	1.67	0.70	2.46	0.71	2.73	9.46	1.65	1.45	4.57	1.28	1.74	5.31	1.21
4	68	44	490	11	1.77	5.08	1.72	0.70	2.48	0.69	2.68	9.73	1.69	1.21	4.43	1.31	1.66	5.19	1.29
5	68	46	540	9	2.00	5.27	1.24	0.68	2.46	0.64	2.97	9.67	1.71	1.32	4.48	1.19	1.78	5.27	1.24
6	68	48	440	10	1.47	5.11	1.42	0.75	2.52	0.65	2.40	9.63	1.76	1.47	4.51	1.24	1.81	5.33	1.31
7	70	44	540	10	1.55	5.14	1.28	0.69	2.48	0.72	2.34	9.78	1.66	1.34	4.40	1.21	1.74	5.22	1.15
8	70	46	440	11	1.70	5.13	1.70	0.71	2.52	0.76	2.57	9.56	1.74	1.48	4.44	1.19	1.79	5.27	1.26
9	70	48	490	9	1.66	5.01	1.29	0.80	2.75	0.89	2.49	9.82	1.79	1.50	4.49	1.29	1.80	5.37	1.30
				Avg	1.70	5.12	1.43	.723	2.56	.766	2.49	9.52	1.71	1.36	4.47	1.22	1.75	5.27	1.23

A : Injection temperature (°C)
C : Injection force (N)
%LS : % Linear shrinkage
SR : Surface roughness (μm)
B : Die temperature (°C)
D : Holding time (min)
%VS : % Volumetric shrinkage

The wax blend 2 with its properties is shown in table 5.3.

Table 5.3: Experimental data with wax blend 2

Expt. No.	Process variables				Measured properties		
	A	B	C	D	Blend 2		
					%LS	%VS	SR
1	66	44	440	9	0.74	2.79	1.09
2	66	46	490	10	0.71	2.56	0.75
3	66	48	540	11	0.70	2.46	0.71
4	68	44	490	11	0.70	2.48	0.69
5	68	46	540	9	0.68	2.46	0.64
6	68	48	440	10	0.75	2.52	0.65
7	70	44	540	10	0.69	2.48	0.72
8	70	46	440	11	0.71	2.52	0.76
9	70	48	490	9	0.80	2.75	0.89
				Avg	0.723	2.56	0.766

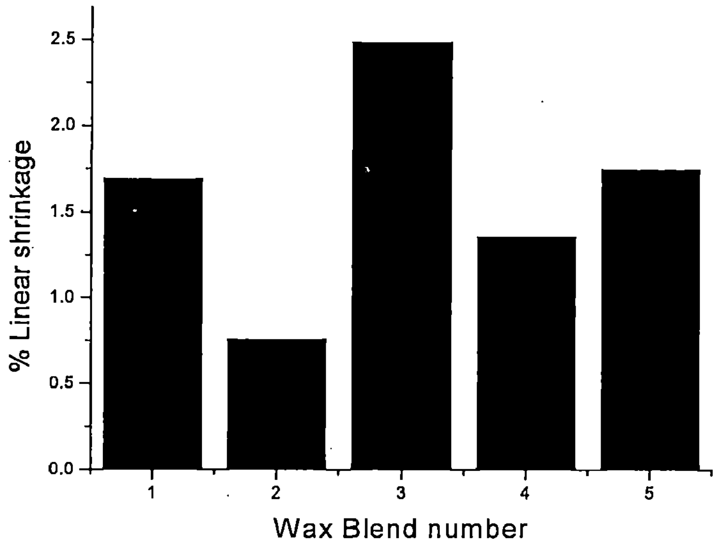


Fig 5.1: Linear shrinkage of wax blends

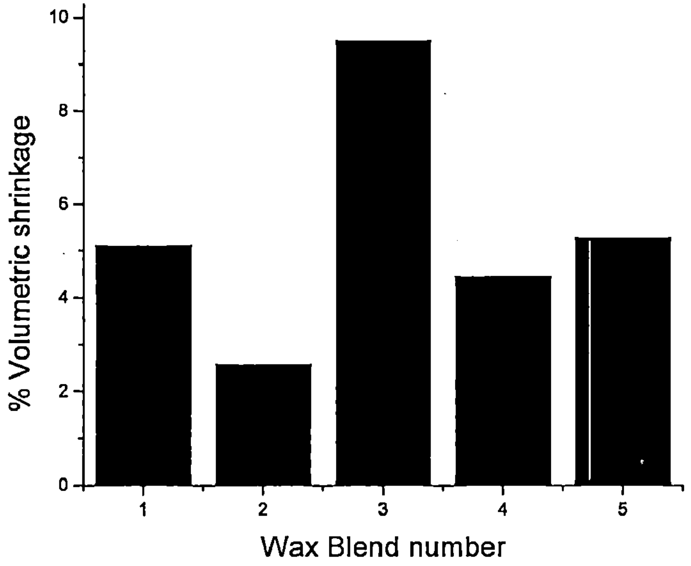


Fig 5.2: Volumetric shrinkage of wax blends

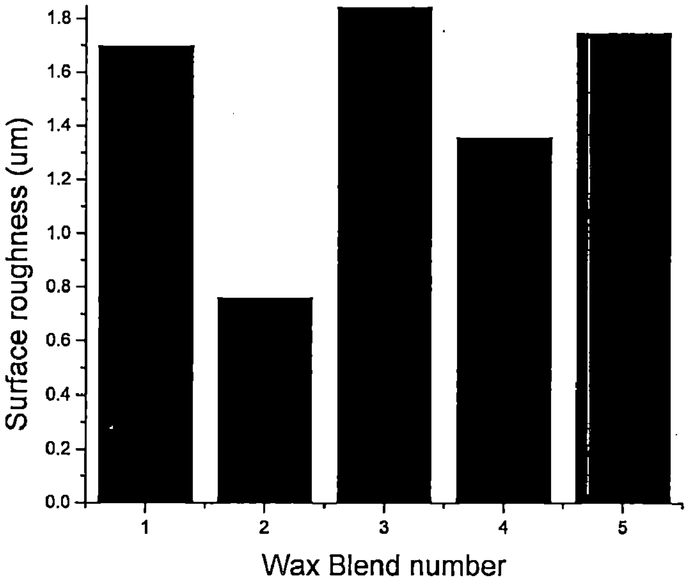


Fig 5.3: Surface roughness (R_a) of wax blends

5.1.1 Effect of process parameters on the linear shrinkage

The effect of process parameters on the linear shrinkage are shown in the following graph (Figure 5.4)

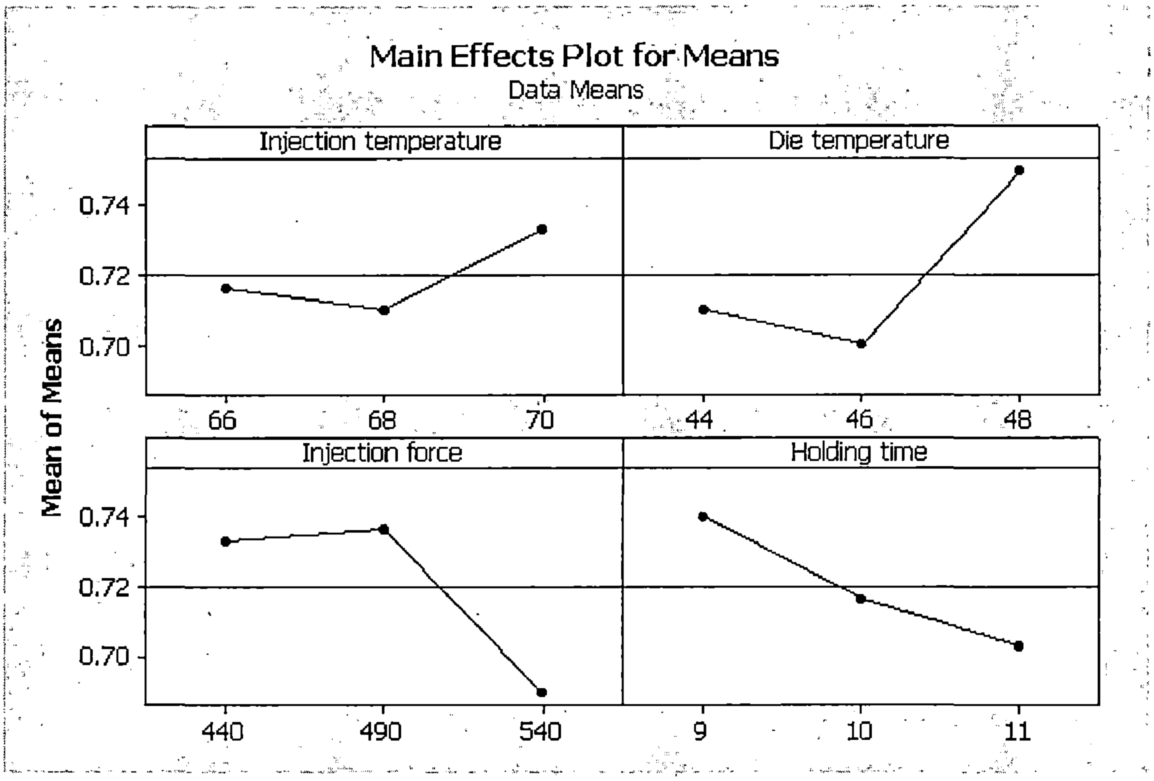


Fig 5.4: Effect of process parameters on linear shrinkage

It is observed from the figure 5.4 that the % linear shrinkage decreases as the injection temperature increase and is minimum at 68 °C. Linear shrinkage increases as injection temperature increases. It is due to high injection temperature results in evaporation of volatile content, some loss of material from wax blend.

As the die temperature increase linear shrinkage decreases this may be due to the reason that with an increase in injection temperature and die temperature an even temperature field exists which causes the wax blend to cool uniformly and results in less shrinkage and is minimum at 46 °C. But further increase in die temperature with an increase in injection temperature increase the linear shrinkage.

Injection force has the positive effect on the linear shrinkage. As the injection force to inject the wax blend into the die increase the linear shrinkage decrease.

Holding time has the positive effect on the linear shrinkage. As the holding time after inject the wax blend into the die increase the linear shrinkage decrease.

5.1.2 Effect of process parameters on volumetric shrinkage

The effect of process parameters on volumetric shrinkage are shown in the following graph (Figure 5.5)

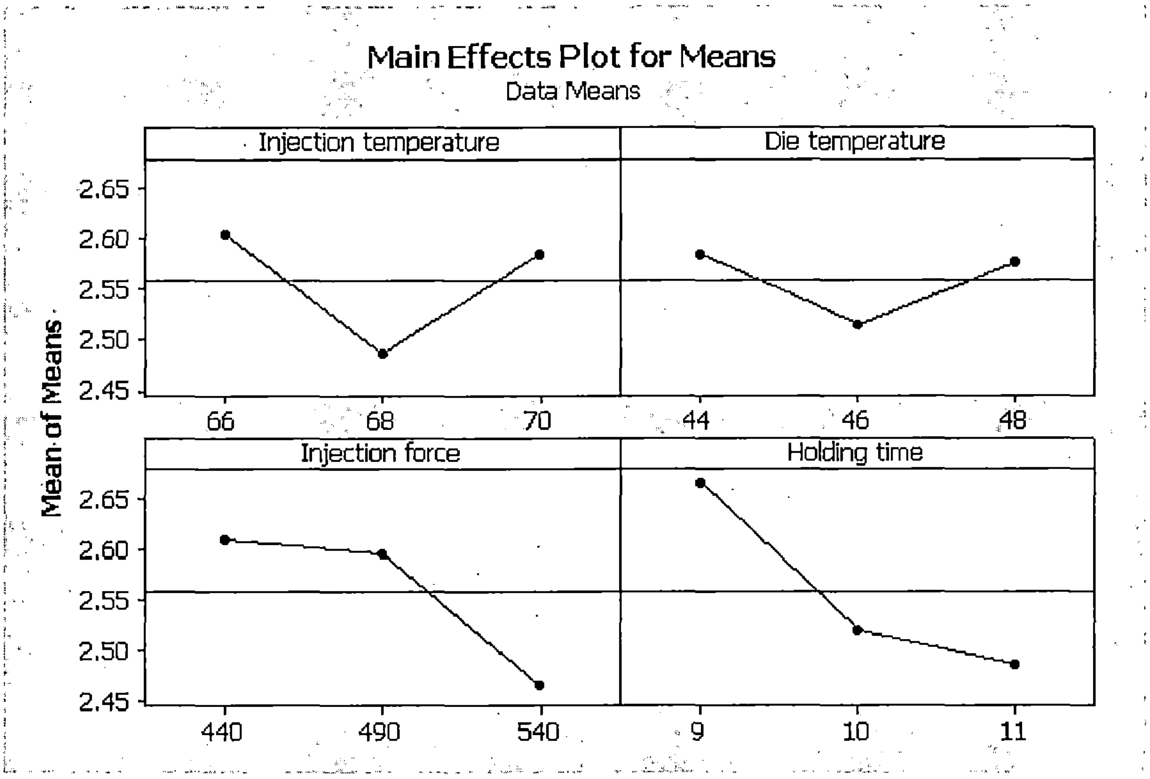


Fig. 5.5: Effect of process parameters on volumetric shrinkage

It is observed from the figure 5.5 that the % volumetric shrinkage decreases as the injection temperature increase and is minimum at 68 °C. Volumetric shrinkage increases as injection temperature increases. It is due to high injection temperature results in evaporation of volatile content, some loss of material from wax blend. The phase transformation of the wax from liquid to solid causes the volumetric shrinkage.

As the die temperature increase volumetric shrinkage decreases this may be due to the reason that with an increase in injection temperature and die temperature an even temperature field exists which causes the wax blend to cool uniformly and results in less shrinkage and is minimum at 46 °C. But further increase in die temperature with an increase in injection temperature increase the volumetric shrinkage.

Injection force and the holding time has the positive effect on the volumetric shrinkage. As the injection force and holding time to inject the wax blend into the die increase the volumetric shrinkage decrease.

5.1.3 Effect of process parameters on surface roughness

The effect of process parameters on surface roughness are shown in the following graph (Figure 5.6)

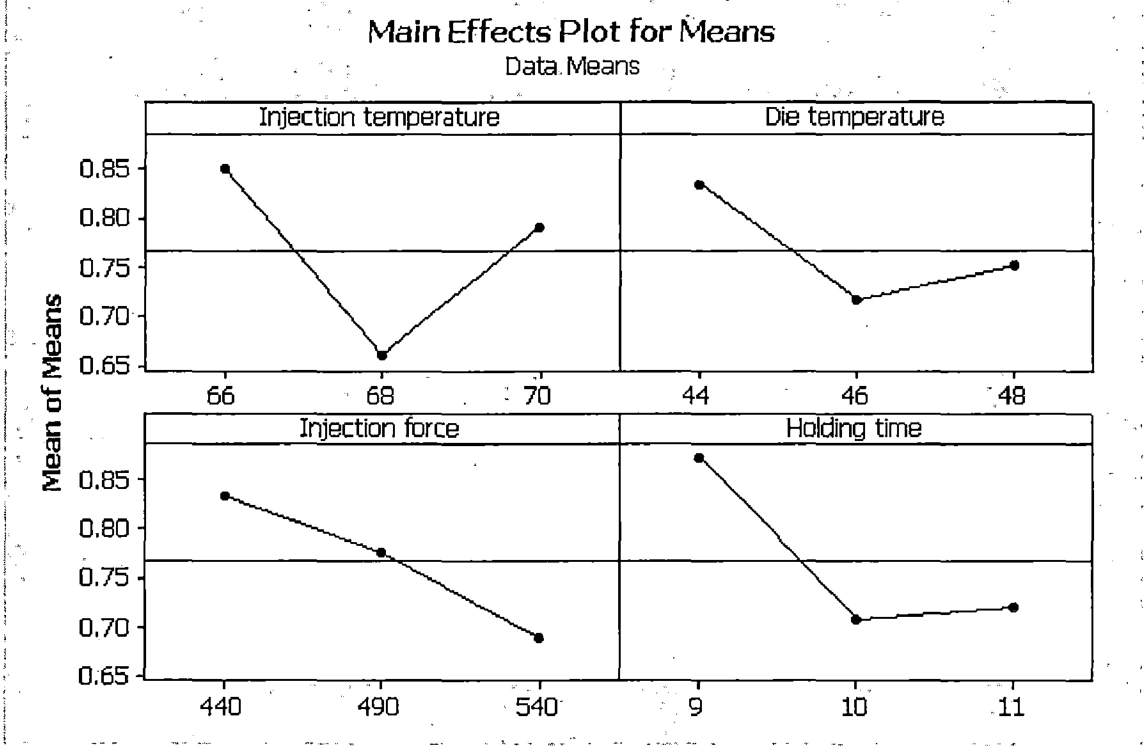


Fig. 5.6: Effect of process parameters on surface roughness

It observed from the figure that increase in injection temperature and die temperature reduces the surface roughness which is minimum at 68 °C and 46 °C. this is due to better replication of the mould surface. Further increase in injection and die temperature increases the surface roughness as reflects the more microscopic features of the mould surface.

The injection force and holding time has the positive effect on the surface roughness. Surface roughness is minimum at 540 N injection force and 10 minute holding time.

5.1.4 The overall effect of process parameters on the responses

After conducting the experiments it is observed that wax blend 2 is giving minimum shrinkage and better surface roughness. Taguchi optimization technique was applied to wax blend 2, using Minitab software. The results of the investigation are shown in Figure 5.7. From the graph of injection temperature (A), it is observed that, as injection temperature increases at 68 °C it gives better results but further increase in injection temperature increases the linear shrinkage, volumetric shrinkage and surface roughness. For graph of die temperature (B), it is observed that at 46 °C it is giving better results. Similarly for graph of injection force (C) and holding time (D), it is observed that these graphs give better results at 540 N and 10 minutes respectively.

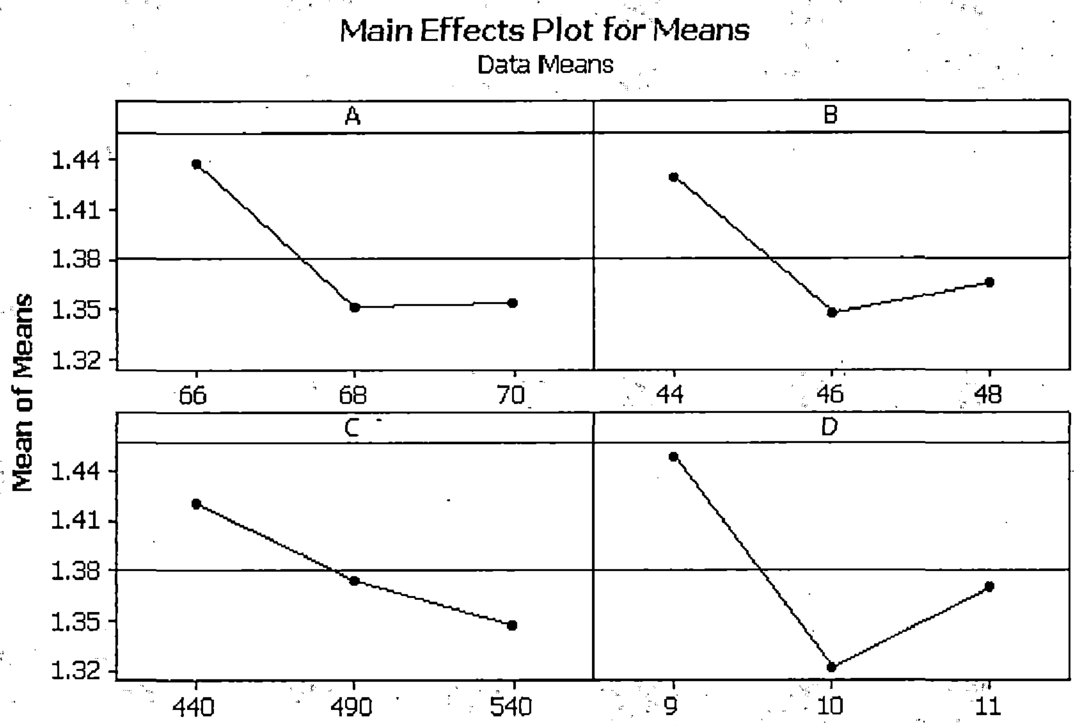


Fig. 5.7: The overall effect of process parameters on the responses

From the graph it is observed that the optimum process parameters to be used are:

Injection temperature: 68 ^{0}C

Die temperature: 46 ^{0}C

Injection force: 540 N

Holding time: 10 minutes

5.2 CERAMIC SHELL PROCESS AND CONTROL

5.2.1 Slurry preparation and control

Slurry preparation and control are major factors that affect the quality of ceramic shell. It important that only well stabilized slurries are used in the construction of ceramic shells. There are number of factors that can affect the stabilization of time from equipment used to slurry makeup techniques. The saving in materials and time are reasons enough to implement the slurry control. The use of slurry control prevents the production of shell from substandard slurries, reducing rework and scrap. The slurry control majors are given bellow.

a) Antifoam test

It is important to test the binder for antifoam content. If antifoam is not at the proper level, it is possible to entrap air in the slurry which can produce week shells. In addition, holes left by the air will fill with metal producing the rough surface. Various conditions, such as high binder solids, can degrade the antifoaming characteristics of the binder. To test for the presence of adequate antifoam:

1. Adding approximately 10-20 ml of binder (binder that has been separated from the slurry) to test tube that can be sealed tightly.
2. Shaking the sample vigorously for 5 seconds.
3. Observing the binder and note the time for foam to dissipate.
4. If the foam breaks in more than 20 seconds, then the appropriate quantity of antifoam is added in slurry.

b) Binder pH Test

Typical colloidal silica based binders operate effectively in a pH range of 9.25-11.0. if the pH is bellow this range, it is an indication that slurry is gelling. Gelling refers to the particles in the binder coming together, thus the binder looses its binder power which results in weak shell.

c) Density test

Properly built and properly maintained slurry should have a consistent density. Density is the weight in grains per unit of volume, usually cubic centimeter, of the slurry. This test may seem unimportant but will indicate if something is happening to the slurry and if further evaluation is required. If slurry density has decreased it can indicate the slurry contain entrapped air.

d) Temperature control

Slurry temperature needs to be monitored for a number of reasons. First of all, high slurry temperatures will speed up the evaporation of water and raise binder solids. At elevated temperatures slurries are more prone to bacterial growth. Wax patterns that are dipped into warm slurries could possibly expand and crack the shell coats. Because of these factors, the temperature of slurry should remain at 20°C +/- 2°C.

Table 5.4: Measured properties of the slurries

Expt. No.	Process variables				Responses		
	Zircon flour (gm)	Filler (gm)	Refractory/ Binder Ratio(gm/ml)	Catalyst (ml)	Viscosity (cp)	Density (gm/ml)	Surface Roughness (μm)
1	150	100	2	3	1508	2.01	3.96
2	150	200	2.5	4	1550	2.10	2.61
3	150	300	3	5	1604	2.14	2.56
4	300	100	2.5	5	1683	2.18	2.68
5	300	200	3	3	1778	2.23	2.25
6	300	300	2	4	1830	2.26	2.98
7	450	100	3	4	1920	2.33	2.71
8	450	200	2	5	1962	2.37	3.25
9	450	300	2.5	3	2075	2.38	2.35

By using the thermometer the temperature can be monitored. If slurry is warm there are few things that can be done. The most common cause for temperature rise is excessive mixing. One solution is to see if the mixer can be slowed down and still keep the refractory in suspension. Alternatively a timer could be put on the mixer so that it is on for a period of time and off for a period of time. A typical cycle of on and off is of five minutes. A final solution to reducing the slurry temperature is keeping the slurry, surrounded by ice, in a bucket. The properties measured after preparation of slurries are listed in the table 5.4.

The dimensions of the casting obtained from different shell produced are listed in the table 5.5.

Table 5.5: Dimensions of the castings

Dimension →	A	B	C	D	E	F	G	H	I
↓castings									
1	94.73	30.28	29.96	34.49	37.77	27.36	18.72	33.96	34.11
2	94.86	30.14	29.87	34.85	38.25	27.99	18.40	33.88	34.09
3	94.30	30.09	29.65	34.56	37.87	27.51	19.03	33.71	33.78
4	94.24	30.11	29.72	34.41	37.95	27.58	19.08	33.84	33.91
5	93.88	29.98	29.45	34.45	37.54	27.42	18.82	33.44	33.96
6	91.97	29.74	29.62	34.61	37.49	27.33	18.30	33.51	33.84
7	94.40	30.05	29.59	34.76	37.56	27.29	18.42	33.41	33.52
8	94.77	29.99	29.92	34.86	37.73	27.37	18.33	33.27	33.89
9	94.62	30.07	30.03	34.52	37.62	27.41	18.65	33.43	33.49

5.2.2 The effect of process variables on slurry viscosity

The slurry viscosity increases as zircon flour increases from 150 gm to 450 gm and is maximum when zircon flour is 450 gm as shown in fig 5.8. Zircon flour has a positive effect on the viscosity of the slurry and, therefore, higher value is desired. The slurry viscosity increases as fused silica increases from 100 gm to 300 gm and is maximum when fused silica is 300 gm as shown in fig. The slurry viscosity increases as refractory/binder ratio increases from 2 gm/ml to 3 gm/ml and is maximum when refractory/binder ratio is 2.5 gm/ml as shown in fig 5.9.

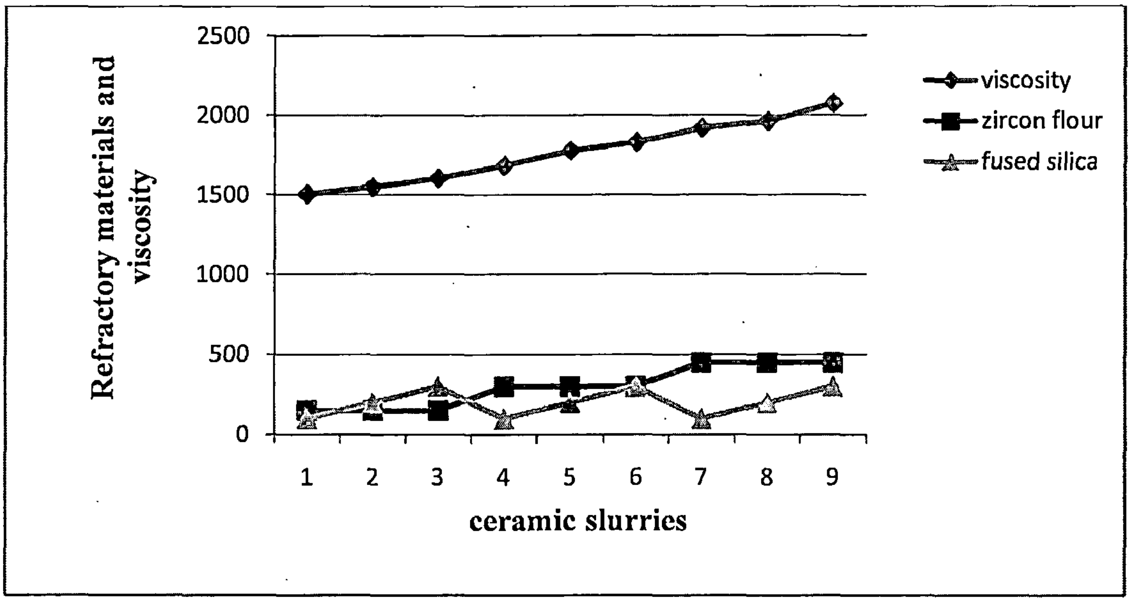


Fig 5.8: Effect of refractory material on viscosity of slurry

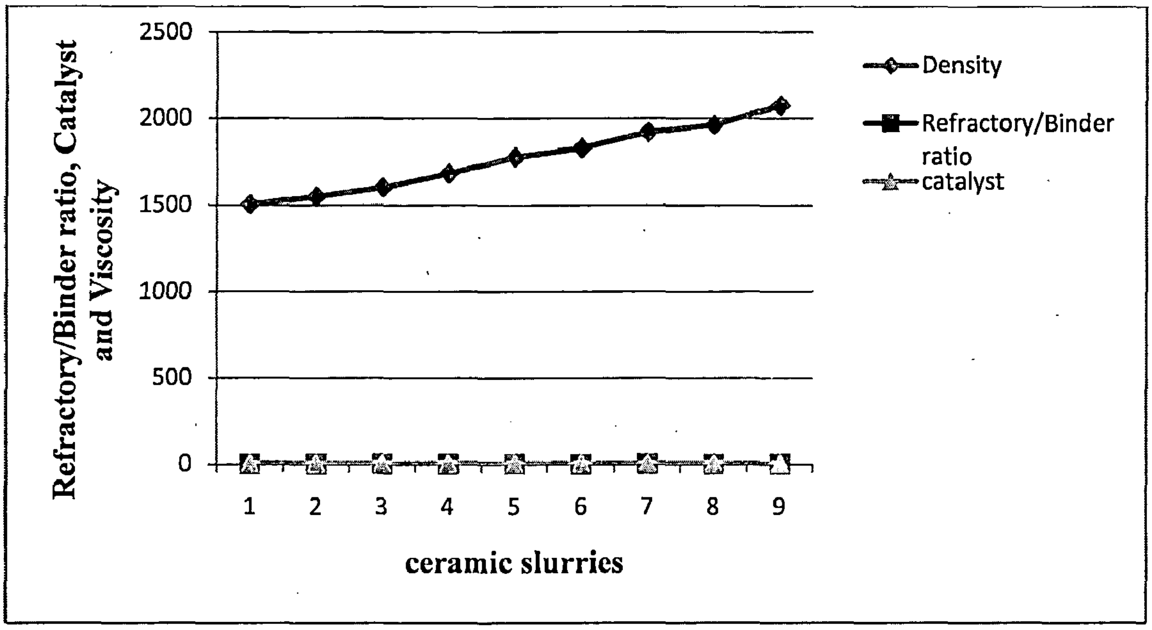


Fig 5.9: Effect of refractory/binder ratio and catalyst material on viscosity of slurry

5.2.3 The effect of process variables on slurry density

It can be observed from Figure that density of slurry increases as the quantity of zircon flour, fused silica, refractory/binder ratio and catalyst increases from first level to third level. It can be seen from figure 5.10, that density increases as quantity of zircon and fused silica is increased from 150 gm to 450 gm and 100 gm to 300 gm respectively. This reveals that peak experimental density occurs at high solid loading. Increase in density is observed as the refractory/binder ratio increases from 2 to 3 as shown in figure 5.11. The catalyst addition is increased from 3 ml to 5 ml. This may be due to the fact that entrapped air in the slurry was removed by the catalyst at this upper level which results in increased density.

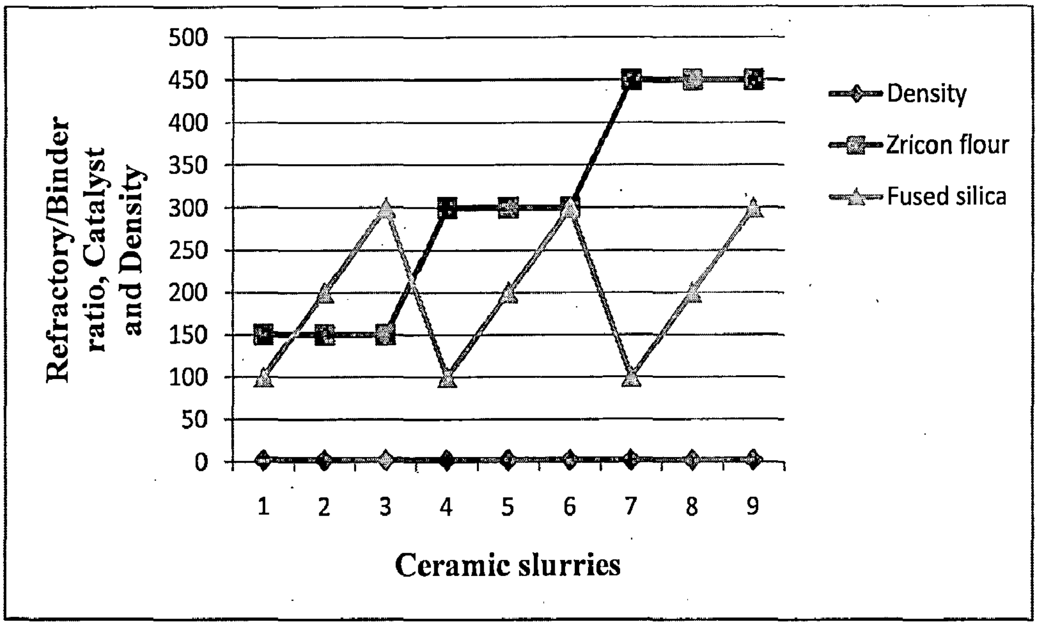


Fig 5.10: Effect of refractory material on slurry density

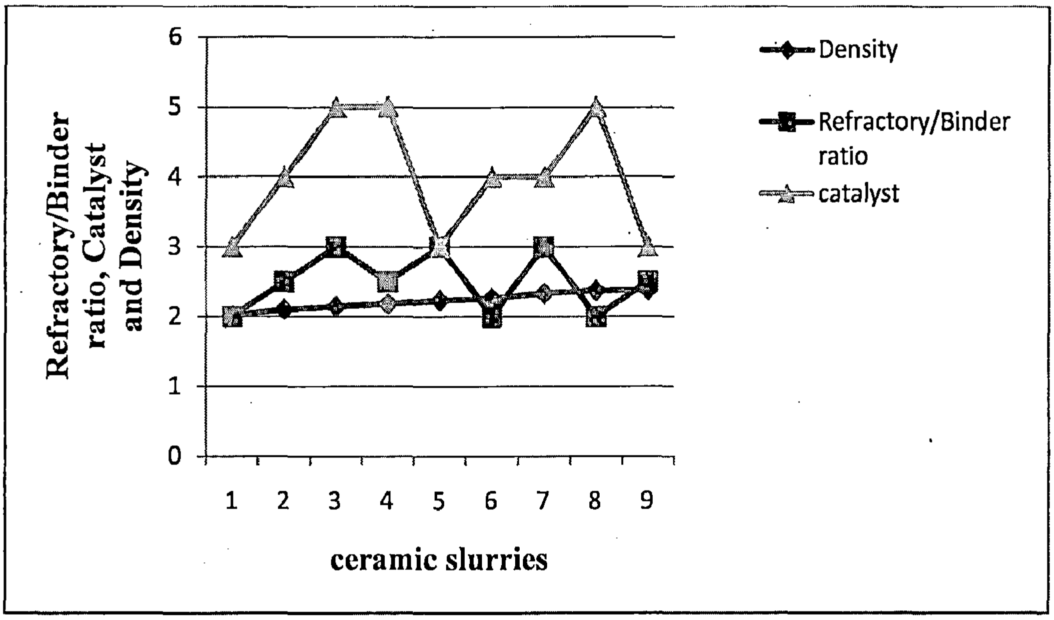


Fig 5.11: Effect of refractory/binder ratio and catalyst material on slurry density

5.2.4 The effect of process variables on surface roughness of casting

The surface roughness of the casting decreases as the refractory material and refractory/binder ratio increases as shown in the figure 5.12 and 5.13. The surface finish normally achieved by this process is in the range of 1.55 – 4.75 microns. All the castings have surface roughness in the required range and improve by increasing binder concentration. Very high binder concentration may drastically affect in reduction of surface area, thus reducing stability of mould and is not desirable.

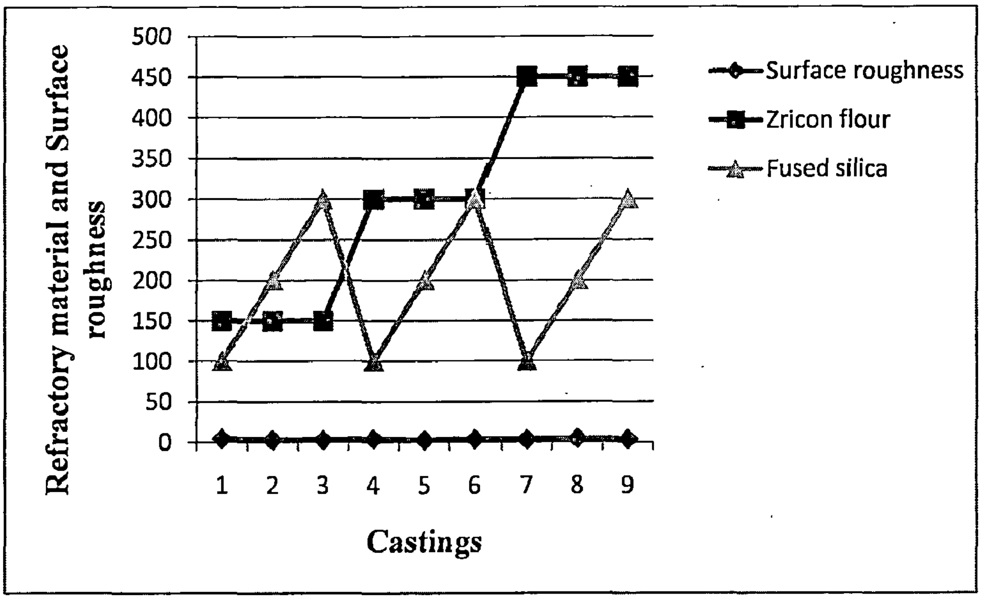


Fig 5.12: Effect of refractory material surface roughness of the castings

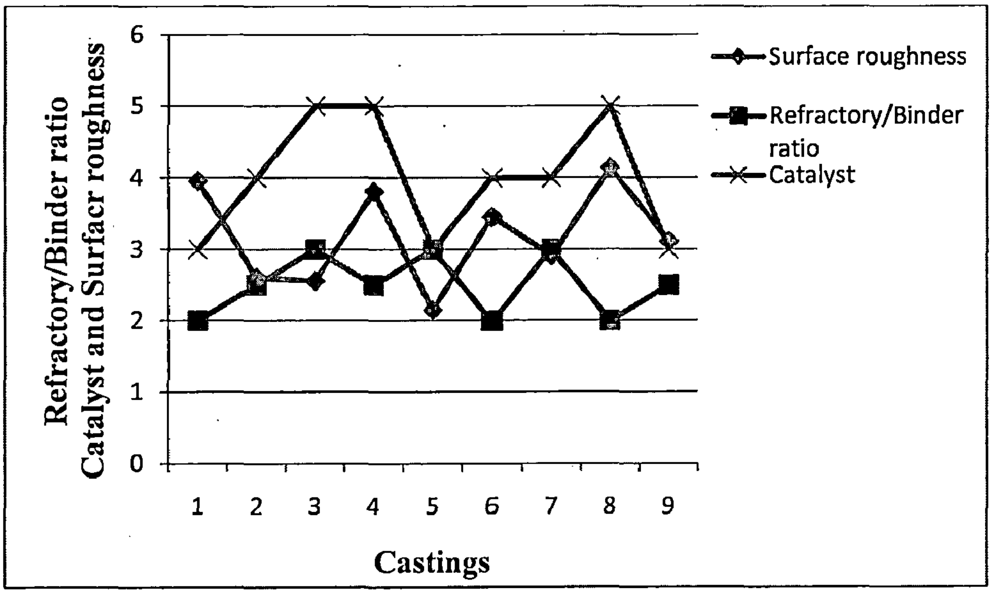


Fig 5.13: Effect of refractory/binder ratio on surface roughness of the castings

5.2.5 Hardness of casting

After casting, the Brinell Hardness of the cast pattern is measured at a load of 62.5 kg with 5mm ball diameter and listed in the table 5.6. It is observed that the hardness values are increasing with increasing refractory and binder material as shown in figure 5.14 and 5.15.

Table 5.6: Hardness of the castings

Expt. No.	Process variables				Hardness of casting (BHN)
	Zircon flour (gm)	Filler (gm)	Refractory/ Binder Ratio(gm/ml)	Catalyst (ml)	
1	150	100	2	3	50.10
2	150	200	2.5	4	52.22
3	150	300	3	5	57.30
4	300	100	2.5	5	62.6
5	300	200	3	3	63.8
6	300	300	2	4	53.63
7	450	100	3	4	71.4
8	450	200	2	5	57
9	450	300	2.5	3	70

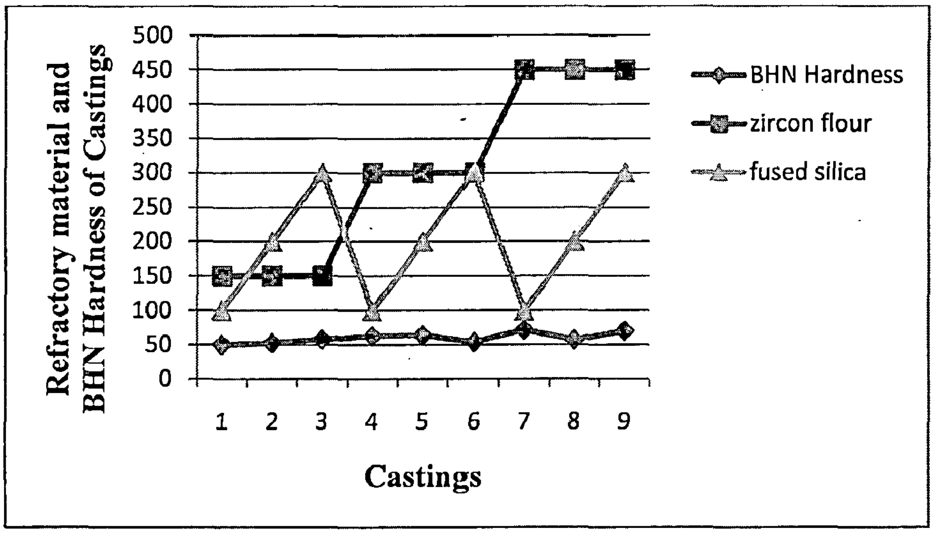


Fig 5.14: Effect of refractory material on hardness of castings

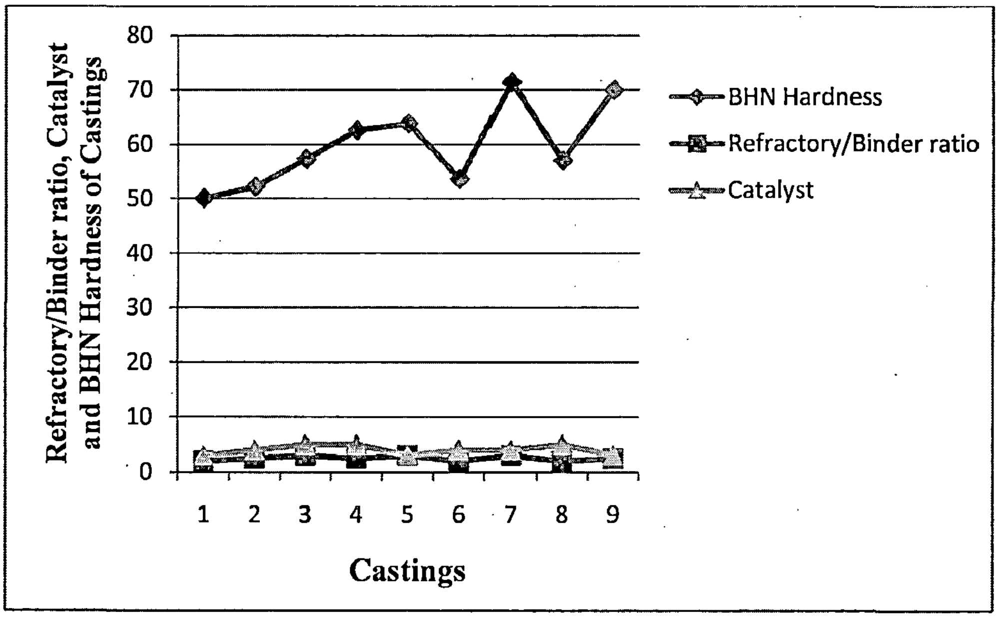


Fig 5.15: Effect of refractory/binder ratio and catalyst on hardness of castings

CHAPTER 6

CONCLUSION AND SCOPE FOR FUTURE WORK

In the earlier chapters, selection of best wax blend, ceramic shell coating characteristics, and casting quality characteristics of the ceramic shell investment casting have been discussed. An optimal set of process variables which yield the optimum quality features has also been obtained.

6.1 CONCLUSION

The conclusions from this work are listed below.

1. Wax blend compositions significantly affect the shrinkage, dimensional accuracy and surface roughness of the patterns.
2. It is possible to enhance dimensional accuracy, shrinkage and surface finish of wax patterns effectively, by controlling wax injection variables.
3. Many companies' uses paraffin wax and bees wax mixture as wax blend having linear shrinkage in the range 1% to 2% and surface roughness in the range of 1 to 3 µm.
4. The wax blend 2 (paraffin wax, bees wax, montan wax in the ratio 50: 30: 20 respectively) has minimum linear, volumetric shrinkage and surface roughness as 0.763, 2.59, 0.764 respectively.
5. The optimum process parameters which gives the minimum shrinkage and surface roughness are as follows;

   Injection temperature 68 °C
   Die temperature 46 °C
   Injection force 540 N
   Holding time 10 minute

6. Changes in the composition of the wax blend can be made to significantly reduce pattern shrinkage and surface roughness and improve manufacturing productivity.
7. The effect of coating material on response characteristics like viscosity, density and surface roughness of the casting are studied. Zircon flour, filler material as fused silica and binder significantly affect the viscosity, density and surface finish.

8. The following optimal values for best coating mixture slurry are as

   Zircon flour: 450 gm
   Fused silica: 300 gm
   Refractory/Binder ratio: 2.5
   Catalyst: 3 ml
   Viscosity: 2075 cp
   Density: 2.38 gm/ml
   Surface roughness: 2.35 µm

6.2 SCOPE FOR FUTURE WORK

The following suggestions for future work

1. The effect of different process parameter on the standardized wax composition should be investigated.
2. Higher order Orthogonal Array (OA) can be considered to incorporate all the possible interactions of the process parameters.
3. Some technique should be developed to maintain desired coating thickness and permeability of ceramic coating.
4. Numerical simulations are required to understand the process and to minimize the time and cost associated in investment casting.

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To Whom It May Concern:

Official Paper Acceptance Notification for WCE 2010

The World Congress on Engineering 2010 (WCE 2010) will take place in London, U.K., 30 June - 2 July, 2010. We are pleased to notify that the below manuscript has been accepted for oral presentation in WCE 2010:

- Author Names: Omkar Bemblage and D. Benny Karunakar
- Accepted Paper Title: A study on the blended wax patterns in investment casting process
- Track and Track Paper Number: ICMEEM_214 (The 2010 International Conference of Manufacturing Engineering and Engineering Management)

Should you have any enquiry, please feel free to contact us.

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