# EXPERIMENTAL STUDY ON EFFECT OF MODERN METHODS FOR DEWAXING CERAMIC SHELL FOR INVESTMENT CASTING PROCESS

**A DISSERTATION**

*Submitted in partial fulfillment of the*
*requirements for the award of the degree*
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**in**
**WATER RESOURCES DEVELOPMENT**

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# CANDIDATE'S DECLARATION

I do hereby declare that the work carried out in the dissertation entitled, **"EXPERIMENTAL STUDY ON EFFECT OF MODERN METHODS FOR DEWAXING CERAMIC SHELL FOR INVESTMENT CASTING PROCESS",** is being submitted by me in partial fulfilment of requirement for the award of degree of "Master of Technology" in Department of Water Resources Development And Management, Indian Institute of Technology, Roorkee is an authentic record of my own work carried out during the period from July 2012 to June 2013 under the guidance of **Prof. GOPAL CHAUHAN,** Department of Water Resources Development and Management , Indian Institute of Technology, Roorkee and **Dr. D.B. KARUNAKAR**, Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee.

This thesis or any matter embodied within this dissertation has not been submitted for the award of any other degree or diploma.

Doli Rani 5·6·13

Date: 5June, 2013 (DOLI RANI)

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# CERTIFICATE

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

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# ABSTRACT

Investment casting is the process well known for achieving excellent finishing of surface, accuracy of dimensions and intricate shapes development. The process parameters behind the preparation of wax blends and ceramic slurry make the investment casting process laborious and troublesome. Due to the thermal expansion, shrinkage of material of pattern, material of mould and solidification of alloy being casted, there are changes that occur between pattern and its corresponding part of casting. Composition of the wax plays a vital role to optimization of the expansion, shrinkage and maximization of hardness of pattern. The ceramic slurry, composition also plays an important role to improve and stabilize the ceramic slurry. The most crucial step in investment casting is the 'dewaxing' of investment shells. It describes the nature of casting because the surface and dimensional traits of the wax are transferred to the shell of ceramic and it leads to the final stage of casting. In the present work, experiments were conducted with different type of waxes namely paraffin wax, microcrystalline wax and carnauba wax, varying their proportion.

The dewaxing of wax from shell was done in microwave and infrared ovens. Using the data obtained from the experiments an attempt has been made to find out the set of input parameters, which could offer a set of ideal properties of 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 those are to be 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. The changes in properties like linear shrinkage, volumetric shrinkage, surface roughness and hardness have been calculated by dewaxing the shell in microwave and infrared ovens.

**Key words:** Investment casting, wax blends, pattern properties, ceramic slurry, Taguchi method, microwave oven, Infrared oven.

# CHAPTER 1
# INTRODUCTION

Investment casting has been in practice as early as 4000 B.C. Modern industry had ignored the technique of investment casting until the end of the 20th century, when the dental profession found it as effective to produce inlays and crowns.

## 1.1 HISTORY

Investment casting is used since long ago. Earliest it was used for making of idols, ornaments and jewellry, by using natural bee's wax for patterns, clay for the moulds and manually-operated bellows for stoking furnaces. There have been a lot of examples found across the world: from Mesopotamia to Mexico and Africa to Egypt, where the detailed artwork of copper, gold and bronze have been done by investment casting process. The Egyptians used the investment casting to make gold jewellery in the time of the Pharaohs (hence named investment) about 5,000 years ago. Complex shapes can be produced with high accuracy.

This technique came into effect as a modern industrial process in late 19th century, when it was used by dentists for making crowns and inlays as mentioned by Dr. D. Philbrok of Council Bluffs, Iowa in 1897.

It's use by Dr. William H. Taggart of Chicago, whose 1907 paper elaborated his development of a technique and designed wax pattern compound of ultrafine properties, produced an investment material and invented an air-pressure based machine for casting.

During World War II in 1940s, the increased demand of précised shape for manufacturing and specialized alloys, the industry moved to investment casting because such desired precision was not possible by traditional methods of manufacturing. After the World War II, the use of investment was casting fully commercialized in industries for intricate metal parts.

The ceramic mould used in investment casting is 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 "Lost-wax process" or "precision casting". Today, Investment casting is a highly précised method of producing near net shape. Its advantages are smooth finishing, reduced machining allowances, close tolerance, flexibility of alloy selection.

In this research work a new technology is used for dewaxing. Here microwave and infrared oven are used for dewaxing of wax from the shell. This process is one of the oldest manufacturing processes. Investment casting is mainly used for manufacturing ferrous and non-ferrous metal parts. Unlike, other traditional methods, investment casting produces much précised net shape parts with appreciable surface finish and dimensional accuracy. This technique can produce intricate shapes that would be quite difficult or impossible with die casting. It can be applied to make parts which are not easy to manufacture by normal manufacturing techniques like turbine blades, aero plane parts which have to sustain the high temperature. The process is generally used for small castings. It is generally more expensive per unit than die casting or sand casting but with lower equipment cost.

## 1.2 STEPS OF INVESTMENT CASTING PROCESS

The main steps of investment casting process are illustrated in Fig. 1.1.

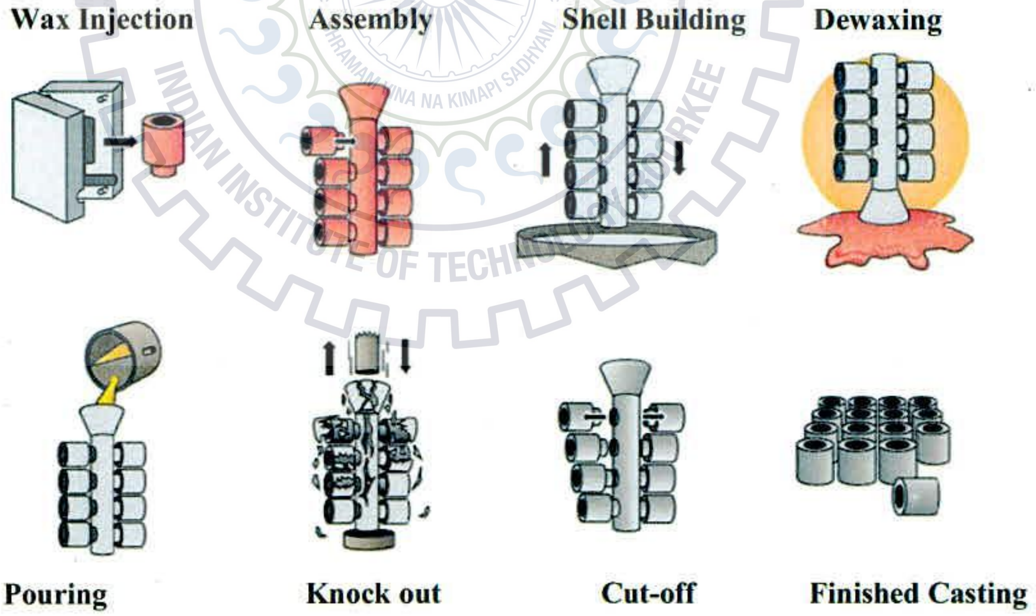

**Fig. 1.1** The main steps in investment casting process

### 1.2.1 Wax injection

Wax is injected into die to produce pattern which may be made up of plastic, tin, frozen mercury or wax, the wax being most commonly used material. Waxes used for preparation of blend are paraffin wax, microcrystalline wax, carnauba wax. The wax is injected at 65-90°C into die using wax injection machine, at a pressure of 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 restrain its shape while being machined and invested.
2. Good wet ability.
3. Resistance to oxidation (this makes the wax to be reused for many times).
4. Low shrinkage so that cast products with high accuracy in the dimension can be produced.
5. It should have good adhesiveness (weld ability) so that the different sections of the 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 ant 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 wax pattern is made individually, these patterns are assembled with a single runner system. Then the wax assembly is prepared.

### 1.2.3 Shell building

The coating of ceramic slurry is done over the assembled wax patterns. The accuracy of metal casting is dependent on the shell building. The material used for shell building should be fine. A mould thus produced should be very strong which can withstand repeated and rapid cycles of cooling and heating.

The wax pattern produced is assembled with single runner system. The multi-component slurry is prepared, which normally composed of a refractory filler system and a binder system.

- **The ceramic slurry contains**

**a) Binders**

There are two type of binders used for ceramic shell systems- water based silica solution or alcohol based ethyl solution. Here water based silica solution is used.

**b) Slurry refractory**

The refractory material is added within the mixture before application to the wax assembly. The added refractory should be of high quality, finely graded mineral flour. The flour disperses throughout the solution to create the wet refractory material known as ceramic slurry.

The refractory material is used to add in to the slurry is zircon silicate flour which is the expensive refractory material. The refractory flour is added to the colloidal solution in very precious proportion. The mixture is then stirred continuously to prevent the refractory from the separating out from the solution and setting in a mass at the bottom of the tank.

After mixing, the slurry is regularly monitored and adjusted to maintain its optimum consistency and quality. Viscosity should also check.

**c) Stucco refractory**

As the refractory materials and mineral flour present in solution, which combines for the formation of 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 serves function which allows the founder to rapidly build up a wall thickness for both structurally strong, and semi-porous to evolved casting gases. Ceramic refractory, referred as STUCCO, is made from fused silica.

### 1.2.4 De-waxing

The moulds are placed in **microwave oven** or **infrared oven**. First of all the wax pattern is melted and the wax is drained from the mould. This drained wax can be reused up to 10-15 cycles. The temperature of microwave should be around 110 °C. Here domestic microwave is used for dewaxing of wax from the shell. The frequency of the microwave oven is 2.45 GHz and the power is 110W. Time of placing blend in the microwave oven is 15 minutes. When dewaxing is done in infrared oven the frequency of infrared oven is 215 THz and the maximum temperature should be 100 °C. Time of placing the wax blend in infrared oven is 30 minutes.

The final step of dewaxing of a ceramic shell is one of the most critical steps in the manufacturing process. In this step the ceramic shell is placed in furnace at temperature of 1000 $^{0}$C to remove residual traces of the wax. After firing process the mechanical strength of the shell will increase. To get the required results, variables such as temperature of the furnace, time of firing, particle size distribution should be considered.

### 1.2.5 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 reheated depending upon the metal to be poured e.g. for light alloys and for steel, the preheat temperature should be of the order of 300 $^{o}$C to 500 $^{o}$ C and 800$^{o}$ C to 1100 $^{o}$ C respectively. Preheated moluds may be filled with molten metal by:

- Under gravity
- Under direct air pressure
- Under centrifugal force

### 1.2.6 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 casting does not get damaged.

### 1.2.7 Cut-off

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

### 1.2.8 Finishing

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

Thus the process of shell building is time consuming because each coat of slurry 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 twenty-eight hours or even more to complete

## 1.3 ADVANTAGES, LIMITATIONS AND APPLICATIONS OF INVESTMENT CASTING PROCESS

### ❖ Advantages

- Possess excellent details, smoother surface, and closer tolerance.
- Freedom of design.
- High production rate.
- Casting does not contain any parting line.
- Intricate shape can be cast.
- Castings produced are sound and free from defects.
- Machining operation can be eliminated thereby attaining considerable saving in cost.
- Thin section can be cast with wall thickness 1 to 2 mm and hole diameter

### ❖ LIMITATIONS

- Production of wax patterns is expensive as compared with other casting.
- Size limitation of the component part to be cast. Most of the casting produced weight 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 in to highly complex shapes such as turbine runner, as shown in Fig 1.2.

**Fig 1.2** Turbine runner

- For making jewellery and art casting, as shown in Fig 1.3.

**Fig 1.3** Jewellery

- Gears and other types of tools, as shown in Fig 1.4.

**Fig 1.4** Gears

- Statue design, etc., as shown in Fig 1.5

**Fig 1.5** Bronze statue

## 1.4 GAP AREAS

- Studies are required to optimize the shrinkage, hardness and expansion of the wax blend. But till now, no study has been reported regarding combination of the wax blends which minimizes shrinkage and expansion. By changing the composition of existing wax blends and by using other additives we can determines the above characteristics.
- Studies are also needed to prepare ceramic slurry which gives better strength and reduce 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.

## 1.5 PRESENT WORK

In the present work, the performance of the waxes and wax blends has been studied by varying the proportion of paraffin wax, carnauba wax and microcrystalline wax. The present study is focused on the reduction of linear shrinkage, volumetric shrinkage, and surface roughness. The study is also aimed to increase the hardness of the wax blend. The study is focused on making process more economical. Dewaxing of the wax from the shell will be done using microwave oven as well as infrared oven.

## 1.6 ORGANISATION OF THE STUDY

- Chapter 1: Covers introductory remarks.
- Chapter 2: Contains Literature review.
- Chapter 3: Contains the Selection of process parameters.
- Chapter 4: Contains experimental setup, experimental work for wax blend, experimental work for ceramic shell.
- Chapter 5: Contains effects of process parameters on linear shrinkage, volumetric shrinkage, surface roughness and hardness, change in properties after dewaxing in microwave and infrared ovens.
- Chapter6: Contains conclusions and scope of the future work

# CHAPTER 2

# LITERATURE REVIEW

Investment casting is growing now a days. During last few years research has been going on for predicting the final casting dimensions. From the literature, some experimental results have been found on the wax blend and shell behaviors.

## 2.1 WAX PATTERNS

**Tascyogylu *et al.* (1)** this paper explains that waxes are the combination of so many compounds including natural or synthetic waxes, solid fillers and even water. Waxes are mixture of natural and synthetic hydrocarbons. This is very difficult to understand their thermo-physical properties. Pattern waxes may be classified into four groups: natural waxes, mineral waxes, mineral waxes, synthetic waxes and paraffin waxes.

**Sabau and Viswanathan (2)** presented a paper which explains the effect of addition of the additives to the wax. The main advantages of using additives are that it gives good dimensional accuracy, increases strength and surface finishing. The additives used may be starch powder, resins, like resins, filler, oils, plastics and plasticizers.

**Okhuysen *et al.* (3)** presented a paper that shows the difference between the pattern dimension and its corresponding cast part's dimension is depend on the shrinkage of the wax. He used computer model to predict the wax dimensions.

**Gebelin and Jolly (4)** explained that the precision- machined full dies should be used where high dimensional accuracy is required. This type of die can be costly. They also concluded that during deciding the dimension of dies the shrinkage allowance should also be kept in mind.

**Bonilla *et al.* (5)** presented a paper that the injection temperature, die temperature, holding time and injection force play an important role in the accuracy of the wax pattern.

**Singh *et al.* (6)** presented a paper "effect of the primary slurry parameters on the ceramic retention test". They calculated the variation in the coating thickness for slurry and ceramic shell moulds made by coating over the wax pattern.The primary coating is done by coarse fused silica sand. The quality of ceramic shell is dependent on the slurry and shell material as well as the process by which the shell is built.

**Liu *et al.* (7)** presented a paper on new investment casting technology, 'freeze cast process' with ice as pattern material. It starts with the building of the solid master and silicone mould. The ice pattern is made from the silicon mould by injecting water in the mould and freezing it. The main advantage of ice pattern is that it prevents shell cracking during pattern removal. Then the ice patern is dipped in to the 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.* (8)** found that most production wax patterns exhibit an abrupt expansion as the crystalline portion of the microstructure melts during de-waxing. The ice pattern can shrink and it can relieve the stress on shell during pattern removal. Because the ice pattern in the FCP process is made from silicon molds, some problem exists, such as multidirectional water expansion during freezing. These problems can be eliminated by making ice pattern with rapid freeze prototyping process.

**Horacek and Lubos (9)** presented a paper "The influence of injection parameters on the dimensional stability of wax patterns produced by injection moulding process". They found relationship between injection parameters like injection temperature; die temperature, injection force, holding time and their dependency on dimensional parameters.

**Yarlagadda and Hock (10)** presented a paper that analysis the accuracy and finishing of the wax pattern produced by soft (RTV mold) and hard (polyurethane mold) tooling and optimized the injection parameters used in a low-pressure injection moulding.

**Tascroglu and Akar (11)** carried out investigations on different additives used in making wax patterns and found that the addition of soybean flours of different varieties or starch powder in to the pattern wax can improve the linear shrinkage, volumetric shrinkage, surface roughness and can improve hardness. The ice pattern gives the better dimensional accuracy and there are less chances of cracking of shell, but it is very difficult to measure surface finish of the ice pattern .Frozen mercury can be used as a pattern material because it does not expand in changing from the solid (frozen) to the liquid state. A major disadvantage of mercury pattern is the requirement for making and keeping them at extremely low temperature and the other disadvantage is its high cost. Ultimately, wax (or wax blend) seems to be the better pattern material which is


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SHRAMAM VINA NA KIMAPI SADHYAM
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available at a lower cost, yet can produce balanced properties. In present research the main types of waxes used are: paraffin wax, carnauba wax and microcrystalline wax.

**Brnett (12)** presented a paper that coating of refractory material on the shell portrays a vital role in lost wax casting process. To ensure no metal penetration and give fine surface to the shell, this technique gives refractory protection. If primary coating is not in proper way then it can increase the number of defects in the casting shell.

**Jones and Marquis (13)** presented a paper that the coating material for preparation of the ceramic shell in lost wax casting process falls in three basic aspects: catalyst and binder, additives and refractory filler. Each aspect has unique objective in producing the entire ceramic shell.

**Beeley and Smart (14)** found that selection of 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 moulds are zircon, fused silica, and aluminium silicate, and they are usually used in combination. Mainly zircon is used for the first coat and fused silica and alumina-silicates are used for other shell coat purpose.

**McGuire (15)** presented a paper that fused silica has too low coefficient of thermal expansion and it is used to create the dimensional stability in ceramic mould. Fused silica is non- reactive filler and it is easy to remove after manufacturing in the finishing and cleanup operations. The thermal shock resistance of fused silica is also good and fused silica is dimensionally quite stable.

**Cui and yang (16)** this paper explained that surface finishing of the cast part, depend on stability in handling of the cluster and quality of the ceramic filler. During coating of the pattern and dewaxing, the cluster must be stable. The viscosity of primary coating slurry and density of ceramic powder determines the quality of ceramic shell.

**Bijvoet (17)** 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. Any formula cannot produce a good casting if the slurry is prepared in the wrong way. Ceramic 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.

**Hendricks (18)** 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 mould cracking, moulds are heated very quickly, so that the surface of the pattern melts before the temperature of the main body of pattern rises. When 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 mould from cracking. Higher the heat input thinner the wax expansion.

**Jones and Yuan (19)** presented a paper that the strength of ceramic shell is depend on mould material, coating procedure, dewaxing procedure, firing procedure etc. Mould filling is improved by increasing the permeability of ceramic shell. The polymer modified binders also reduce the fired strength due to burn out of the organic phase which in turn by increasing the permeability decrease possibility of misrun or non fill of casting.

**Roberts *et al.* (20)** presented a paper which carried out a survey of 11 shell system 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.

**Baumeister *et al.* (21)** explained "The influence of casting parameters on the microstructure and the mechanical properties of extremely small parts produced by micro-casting". In this paper the micro tensile test of the work piece produced by vacuum pressure casting and centrifugal casting.

**Rafique (22)** the paper explained the heat transfer during solidification and the metal properties obtained after solidification. It is observed that improper heat transfer and improper molding materials and casting condition can increase the defects such as shrinkage, porosity, cold shut, pin holes, air holes etc. They used a mathematical model using standard transport equations incorporating all heat transfer coefficient to calculate the solidification time of the material and computer simulation of the model is carried out in C++ to validate the model.

**Sabau** ***et al.*** **(23)** explained that wax, zircon prime coat and fused silica are used for preparation of the shell mould in investment casting process. The dimensions of wax pattern die and casting patterns are measured by coordinate measurement machine (CMM). They used numerical simulation for obtained the dimensions.

**Bemblage** ***et al.*** **(24)** explained that experiment is conducted with four types of wax namely bees wax, paraffin wax, montan wax and carnauba wax with varying percentage. In each case properties of wax pattern is measured. They used Taguchi method to find out the set of input parameters. The parameters suggested by Taguchi method were verified and found to offer the set of desired optimal properties of the wax blend properties.

## 2.2 CERAMIC SHELL

All ceramic shell moulds are built up from three components: the binder, filler and stucco materials. Some of the important parameters of an investment casting mould include: green strength, fired strength, thermal shock resistance, chemical stability, mould permeability and thermal conductivity. These materials are zircon flour which is often used for the first coat while fused silica and alumina- silicate are used for secondary coats. The binders used are colloidal silica, ethyl silicate, liquid sodium silicate etc. The ingredients 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 the zircon sands are round in shape and 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 AFSGFN 90 TO 130and 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:

- High refractoriness, which increase with increase alumina content.
- High mechanical strength at high temperature.
- Greater resistance to corrosion.
- Less reactive toward many alloys.

### Aluminium silicate

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

### Fused silica

The sand which forms the major portion of moulding sand (up to 96%) is essential the silica grains. It has been widely used as a refractory for ceramic shell moulds, because of low thermal expansion. The sand grains may vary in size from a few micro meters to a few millimetres. Shapes 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 binders is to produce cohesion between refractory grains in the dried state, since bonding materials are not highly refractory. Commonly use binder in investment casting process is:

a) Ethyl silicate
b) Colloidal silica

Excellent surface are obtained with colloidal silica as bonding material. It is manufactured by removing sodium ions from sodium silicate by ion exchange.

## 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 drying which require 8 to 24 hours.

Many wax blends are used to test for the shrinkage characteristics and its effects on the final dimension of the pattern and casting product. The accuracy of the wax pattern depends on injection temperature. These parameters are the injection temperature, injection pressure, die temperature and injection cycle time.

The important parameters of investment casting mould include: green strength, fired strength, thermal shock resistance, chemical stability, mould permeability and thermal conductivity. The removal of the wax from an unfired ceramic shell system without cracking or dimensional alterations is a key stage of investment casting process. Dewaxing of wax from shell is also play a vital role in accuracy of the product. The new technology can be used for dewaxing of wax from shell. In this research work I am using microwave and infrared oven for dewaxing of wax from shell.

The Taguchi method is used to find out the set of input parameters. The parameters suggested by Taguchi method are verified and found to offer the set of desired optimal properties of the wax blend properties.

# CHAPTER 3

# SELECTION OF PROCESS PARAMETERS

In this chapter the selection of process variables, which may affect the casting quality are described. The wax pattern quality characteristics, pattern coating material characteristics and casting quality characteristics are measured. The ranges of process variables are decide 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 centuries. His method focuses on the effective application of engineering strategies rather than advanced statistical technique.

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

a) Quality should be designed in to the product and not in to 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 standards and the losses should be measured system- wide

### 3.1.1 Experimental design strategy

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

- 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:

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

$(DOF)_R$= degree of freedom

P=number of factors

L= number of levels

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

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** Orthogonal Array $L_9$

| **Exp. 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 numbers of levels.
- Selection of appropriate orthogonal array.
- Assignment of factors to the columns.
- Conduct the experiment.
- Analyze the result.

## 3.2 SELECTION OF WAX BLEND PARAMETERS

Accuracy of final casting product is depending on the accuracy of wax pattern. Production of adequate patterns is more important in the investment casting process. Therefore use of optimum wax proportion which gives minimum shrinkage and surface roughness is of considerable importance .The waxes used and their proportions are given below.

### 3.2.1 Wax used

Pattern waxes are blends consisting of components such as:

- Paraffin wax
- Carnauba wax
- Microcrystalline wax

**a) Paraffin wax**

Paraffin is a class of aliphatic hydrocarbons characterized by straight or branched carbon chains, generic formula $C_nH_{2n}+2$. Their physical properties vary with increasing molecular weight from gases to waxy solids. Paraffin waxes are white, translucent, tasteless and odourless solids consisting of a mixture of solid hydrocarbons of high molecular weight. These are soluble in benzene ligroin and warm alcohol. The property of paraffin wax is that it gives better surface finish

**b) 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%). The main property of this wax is that, it gives better dimensional accuracy.

**c) Microcrystalline wax**

Microcrystalline waxes are a type of wax produced by de-oiling petrolatum, as part of the petroleum refining process. In contrast to the more familiar paraffin wax which contains mostly unbranched alkynes, microcrystalline wax contains a higher percentage. The properties of different type of waxes used are given in table 3.2.

**Table 3.2** Properties of the waxes used

| SR NO. | NAME OF WAX | DENSITY (GM/CC) | MELTING POINT ($^0$C) | VOLUMETRIC SHRINKAGE (%) | VISCOSITY (CP) | REMARK |
|---|---|---|---|---|---|---|
| 1 | Paraffin wax | 0.78 | 64 | 6.20 | 32 | Better surface finish |
| 2 | Carnauba wax | 0.99 | 87 | 4.20 | 40 | Good dimensional accuracy |
| 3 | Microcrystalline wax | 0.83 | 82 | 3.82 | 10.2 | Good surface finish |

### 3.2.2 Wax composition

Preparation of wax is the starting point of the investment casting process. An important consideration in selection of wax composition for investment casting pattern is that it must have consistency and dimensional stability .One serious problem of wax material is that it undergo for large and uneven shrinkage. In present study an effort has done to improve the quality of cast part. The three types of waxes (paraffin, carnauba, microcrystalline) with their melting temperature, densities, volumetric shrinkage and viscosities are mentioned in table 3.2.

The proportions selected in the formation of the wax blend are given in the table 3.3.

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

| BLEND NO. | PARAFFIN WAX | CARNAUBA WAX | MICROCRYSTALLINE WAX |
|---|---|---|---|
| 1 | 40 | 40 | 20 |
| 2 | 40 | 20 | 40 |
| 3 | 50 | 50 | 0 |
| 4 | 60 | 20 | 20 |
| 5 | 70 | 10 | 20 |

### 3.2.3 Pattern based process variable

Patterns are made by injecting the wax into the die. One of the key demands for better tolerance in the lost wax casting is to analysis the shrinkage and reduces the shrinkage of pattern material to improve the accuracy of product. The following process variables are selected to visualize their effect on the dimension accuracy and surface roughness of the wax pattern.

- Injection temperature
- Die temperature
- Injection force
- Holding time

The above process variables are selected to visualize their effect on dimensional accuracy, surface finish, and linear, volumetric shrinkage and hardness of the wax pattern produced for investment casting process and range of parameters are in given table 3.4.

**Table 3.4** Range of process parameters

| PROCESS PARAMETERS | RANGE | LEVEL | | |
|---|---|---|---|---|
| | | L1 | L2 | L3 |
| Injection temperature (A) | 65-90°C | 65 | 70 | 75 |
| Die temperature (B) | 44-48°C | 44 | 46 | 48 |
| Injection force ( C) | 440-540N | 440 | 490 | 540 |
| Holding time (D) | 8-15 min. | 8 | 10 | 12 |

## 3.3 SELECTION OF CERAMIC SHELL PARAMETERS

Selection of materials for shell is important to successful production of high quality cast parts. Shell material need to be of sufficiently high refractoriness. The shell material used, their ingredients are given below.

### 3.3.1 Slurry material

The materials used for preparing the slurry are as follows:

#### a) Zircon flour

Zircon flour is the mineral zirconium silicate ($ZrSIO_4$). It is the primary source of investment casting shell mould. Its major advantages are:

- High refractoriness, which increase with increase in alumina content.

- Less reactive toward many alloys.
- Greater resistance to corrosion.
- High mechanical strength at high temperature.

**b) Filler**

Aluminium silicate is the common filler material used. It is a mixture of 42% to 70% 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 moulds, because of low thermal expansion. The sand grains may vary in size from a few micrometers to a few millimetres. Shapes of grains may be rounding, sub-angular and angular. The size and shapes of these sand grains greatly affect the properties of moulding sand.

**c) Binder**

Binder is used to produce cohesion between the refractory grains. The required strength must be obtained with minimum possible addition. Commonly used binder in investment casting process is colloidal silica. Excellent surface is obtained with colloidal silica as bonding material. It is manufactured by removing sodium ions from sodium silicate by ions exchange.

**d) Catalyst**

The catalysts used are n-octal alcohol and triton, which act as antifoaming agent.

### 3.3.2 Slurry based process variables

The coating material for preparation of ceramic shell in investment casting fall in four aspects: binder, catalyst, refractory and additives. Each category has unique traits and objective in producing the entire ceramic mould. Refractory coating plays a vital role in ceramic shell lost wax casting. The three most commonly used refractories for ceramic shell moulds are zircon, fused silica and aluminium silicate, and they are usually used in combinations.

Following variables are 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 are 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 quantities of conducting the experiments are decided on the basis of literature review (24) and are as shown in the table 3.5.

**Table 3.5** Quantity of process variables

| PROCESS VARIABLES | QUANTITY |
|---|---|
| Zircon flour (gm) | 450 gm |
| Filler materials (gm) | 300 gm |
| Binder ratio (ml) | 2.5 |
| Catalyst (ml) | 3 ml |

After preparing the slurry by using above combinations, Coating of wax pattern is done. After dewaxing the shell and 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 after solidification final product is ready.

# CHAPTER 4

# EXPERIMENTAL WORK

Investment casting process has three major stages. 1. Manufacturing of wax pattern, 2. Manufacturing of the ceramic moulds and 3. Manufacturing of metal product. The main purposes of pattern die is to produce wax patterns by injecting wax into die. The wax patterns are used to produce a ceramic shell by the application of a series of ceramic coating, and the alloy is cast into the de-waxed shell mould. Since an expandable pattern without split lines is used, limitations on design complexity are minimized.

## 4.1 EXPERIMENTAL SETUP

The whole setup is divided into the following parts:

i) Pattern dies

ii) Wax injection machine

- Wax melting unit
- Wax injection unit
- Die clamping unit

iii) Slurry mixture and holding tanks

iv) Dewaxing device

### 4.1.1 Pattern die

Dies may be made 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. The dies thus formed, achieve the highest standard of accuracy and have considerable long life. Dies of low melting points 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 die or mould by embedding it in plaster or clay and casting one die half at a time by pouring a low melting alloy such as bismuth or lead. Die halves are sent for necessary machining and drilling the gate through which wax is to be injected for preparing expandable pattern. Sunk dies are more costly than cast dies for short production runs.

For sake of simplicity, it was decided to select a die capable of producing only a single pattern weighting approximately 150 gm. The master pattern used in the present study is shown in figure 4.1. It is used to produce two halves of the die. The master pattern is given an allowance for subsequent contractions of pattern and metal. All the surface details have been included in the die itself. Aluminium 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 melted wax and injected in to die for production of wax pattern. Injection machine is classified by a state of the wax that the machine is capable of injecting. Plunger type machine is used in present research work. Equipments of the wax injection unit are shown in figure 4.2 and 4.3. The machine is usually limited to pressure less than 650 kpa, only injects liquid wax for large variety of small parts. The temperature of wax injection can be controlled by controlling the temperature of wax in reservoir and in the nozzle. In horizontal injection system, the wax is injected in a straight line from the injection cylinder through nozzle into the die.

The injection machine (Fig 4.2) which is fabricated for present work, has three main components: The wax melting unit, wax injecting unit and the die clamping unit as described below:

**Fig 4.2** Wax injection machine

**a) Wax melting unit**

It consists of thin tapered wall aluminium containers. 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 is used to heat the wax. A temperature sensor is used to measures the injection temperature. A stirrer is fitted to the centre of top cover plate and is extended to the bottom of the reservoirs without touching its surface.

**b) Wax injection unit**

As shown in figure 4.3, a cylinder is fitted with nozzle on front side and closed with rubber seal on its back side, while plunger remains inside the cylinder. One die can be loaded at a time to the wax injection unit.

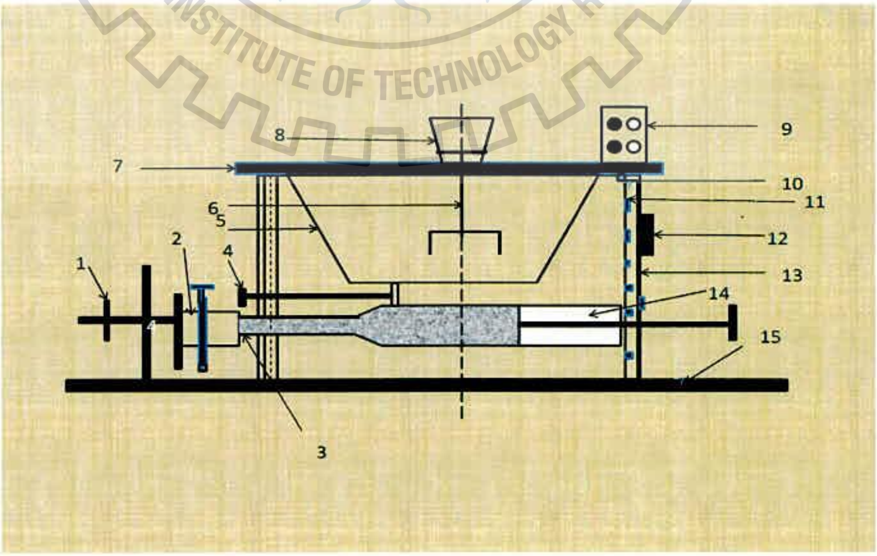

**Fig 4.3** Wax injection machine (1. Die clamp, 2. Die, 3. Nozzle, 4. Control valve, 5.Wax reservoirs, 6.Stirrer, 7.Cover plate, 8.Electic motor, 9. Temperature controller,

10. Asbestos sheet, 11. Heating coils, 12. Power supply, 13. MS sheet, 14.Clinder and plunger, 15.Base plate).

### c) Die clamping unit

The function of die clamping unit is to load and unload the die into the injection nozzle. As shown in figure 4.3.

### 4.1.3 Slurry mixture and holding tanks

Slurry mixer is used to mix the refractory filler and binder to produce stable viscosity of the slurry. A moderate shear propeller type slurry mixer is used for this research work.

### 4.1.4 Dewaxing device

The primary objective of dewaxing 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. Here microwave and infrared oven is used for dewaxing of wax from shell. The dewaxing devices are shown in figure 4.4 and 4.5.

**Fig 4.4** Microwave oven

**Fig 4.5** Infrared oven

The main advantage of dewaxing by using microwave oven and infrared oven is that no purification treatment is required on the resulting wax. Dewaxing by using microwave and infrared oven is repeated up to 9 cycles. We are using microwave oven for dewaxing of wax pattern. The wax model is placed inside a domestic microwave oven.

The frequency of microwave oven is 2.45 GHz and power of 1100 W, for time of 15 min at room temperature and pressure of 1 atm, reaching a maximum temperature of 110 ° C .The main advantage of dewaxing by using microwave is that no purification treatment is required on the resulting wax. Dewaxing by using microwave is repeated up to 10-15 cycles. In infrared oven, there are 4 bulbs of 250 watts to produce the thermal effect for dewaxing the blend at the constant temperature. The frequency of infrared is 215 THz for dewaxing, the blend is placed in hanger and a vessel is placed below the hanger, so that melted wax is dropped slowly into the vessel. The time taken for total dewaxing is 30 min. The stored melted wax is used again and again for recycling purposes up to 9 times.

The properties of the wax will significantly change after repetitive dewaxing cycle. After dewaxing process the same wax can be used for next cycle without purification. The main advantage of microwave oven and infrared oven is the same wax can be used up to 10-15 cycles. Cost of these equipments is less and they are environmental friendly.

## 4.2 EXPERIMENTAL WORK FOR WAX BLEND

### 4.2.1 Mixing of wax blends

The main types of waxes (paraffin wax, carnauba wax, microcrystalline wax) with different melting temperature in between 65-90 °C are selected for the present study. All waxes are 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 °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 °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 the molten wax can be injected into the die. The die is heated up to 48 ° C before injecting the wax and the wax injection temperature is maintained up to 75 ° C.

### 4.2.3 Withdrawal of pattern

As the wax enters the die, die temperature increases further. The time required to withdraw the solidified wax pattern from the die is near about 8 min to 12 min. The wax pattern removed from die is as shown in figure 4.6. If the pattern is removed before this time there is chance of breakdown of the pattern in the two separate halves of the die. The parameters customarily controlled include wax temperature, injection temperature.

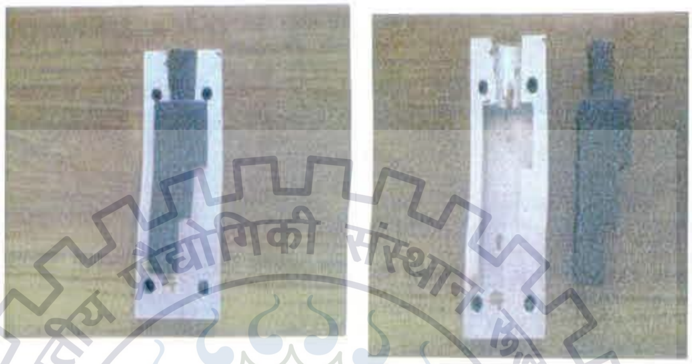

**Fig 4.6** Withdrawal of pattern from die

### 4.2.4 Measurement of properties

After the pattern production the following properties are measured.

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

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

- Injection temperature 65 °C to 75 ° C
- Die temperature 44°C to 48 °C
- Injection force up to 440 N to 540 N
- Holding time up to 8 min to 12 min.

The average shrinkage of pattern dimension is calculated from the measured data.

**1) Linear shrinkage**

Linear shrinkage can be calculated by measuring the difference between die dimension and pattern dimension.

**2) Volumetric shrinkage:** The volumetric shrinkage is calculated as follows:

i. 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.

ii. Fill the die cavity with water and measure its volume with the help of a measuring flask. ($V_D$)

iii. Fill water in a measuring flask and note the initial reading ($V_i$).

iv. Place the wax patterns made inside the measuring flask, volume rises and take the final reading. ($V_f$)

v. The difference between the two readings ($V_f - V_i$) gives the volume of pattern.

vi. The percentage of volumetric contraction of the pattern is given by following equation;

$$\frac{\{V_D - (V_f - V_i)\}}{V_D} \times 100$$

Volumetric coefficient of thermal expansion is calculated by the relationship as shown.

$\Delta V = \beta \, V_i \, (Ti - T_f)$

Where, $\Delta V$ = change in volume

$\beta$ = volumetric coefficient of thermal expansion

$V_i$ = initial volume,

$T_i$ = initial temperature,

$T_f$ = final temperature

**3) Surface Roughness**

Surface roughness of the each pattern is measured by using Optical Profiling System device as shown in figure 4.7, which is of the type Veeco WYKO NTI 100.

**Fig.4.7** Optical profile meter

**4) Hardness**

Hardness of each pattern is measured by using Penetrometer as shown in figure 4.8.

**Fig 4.8** Penetrometer

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

**Table 4.1** The Orthogonal Array used to produce the pattern

| Exp. No. | Process variable | | | |
|---|---|---|---|---|
| | Injection temperature ($^oC$) | Die temperature ($^oC$) | Injection force (N) | Holding time (min.) |
| 1 | 65 | 44 | 440 | 8 |
| 2 | 65 | 46 | 490 | 10 |
| 3 | 65 | 48 | 540 | 12 |
| 4 | 70 | 44 | 490 | 12 |
| 5 | 70 | 46 | 540 | 8 |
| 6 | 70 | 48 | 440 | 10 |
| 7 | 75 | 44 | 540 | 10 |
| 8 | 75 | 46 | 440 | 12 |
| 9 | 75 | 48 | 490 | 8 |

The dimensions of patterns obtained from the different wax blends are listed in the following tables from table no. 4.2 to 4.6 Here Pij, i=wax blend number and j= pattern number and the dimensions A, B etc are shown in the sketch below.

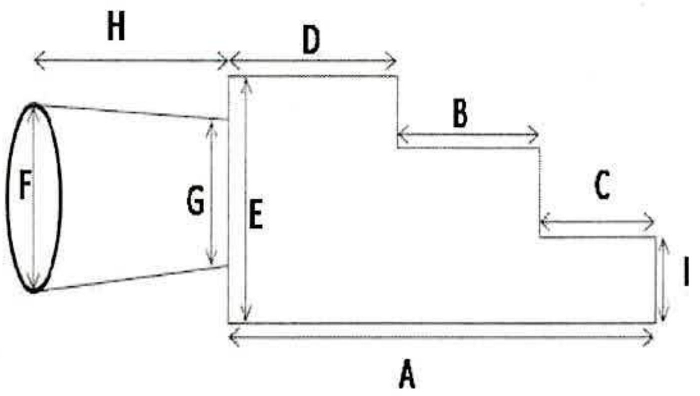

Table 4.2 Pattern dimension obtained from Blend 1

| Dimension | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| Die dimension | 96.98 | 30.85 | 30.65 | 35.98 | 38.60 | 28.28 | 19.56 | 35.40 | 34.50 |
| P11 | 95.85 | 30.02 | 30.59 | 35.25 | 38.57 | 28.09 | 19.25 | 35.12 | 34.45 |
| P12 | 96.58 | 29.85 | 30.39 | 35.24 | 38.55 | 28.17 | 19.45 | 34.23 | 34.42 |
| P13 | 96.51 | 30.55 | 30.44 | 35.19 | 38.55 | 27.06 | 19.49 | 34.36 | 34.34 |
| P14 | 96.12 | 30.10 | 30.58 | 35.66 | 38.28 | 27.17 | 19.35 | 34.16 | 34.40 |
| P15 | 96.07 | 29.45 | 30.60 | 35.67 | 38.43 | 27.13 | 19.35 | 34.37 | 34.36 |
| P16 | 96.15 | 30.55 | 30.19 | 34.56 | 38.18 | 27.18 | 19.12 | 34.28 | 34.32 |
| P17 | 96.86 | 30.11 | 30.45 | 35.23 | 38.34 | 27.80 | 19.23 | 34.18 | 34.41 |
| P18 | 96.56 | 30.13 | 30.59 | 35.24 | 38.53 | 27.70 | 19.28 | 34.28 | 34.20 |
| P19 | 96.12 | 30.19 | 30.22 | 35.45 | 38.50 | 28.18 | 19.37 | 34.54 | 34.34 |

**Table 4.3** Pattern dimension obtained from Blend 2

| Dimension | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| Die dimensions | 96.98 | 30.85 | 30.65 | 35.98 | 38.60 | 28.28 | 19.56 | 35.40 | 34.50 |
| P21 | 96.56 | 30.24 | 30.46 | 35.29 | 38.51 | 28.11 | 19.24 | 34.25 | 34.48 |
| P22 | 96.12 | 30.26 | 30.45 | 35.30 | 38.29 | 28.15 | 19.20 | 34.27 | 34.47 |
| P23 | 96.18 | 30.28 | 30.56 | 35.28 | 38.22 | 27.19 | 19.21 | 34.19 | 34.37 |
| P24 | 96.67 | 30.30 | 30.34 | 35.20 | 38.45 | 27.12 | 19.32 | 34.29 | 34.38 |
| P25 | 96.23 | 30.29 | 30.33 | 35.30 | 38.52 | 27.12 | 19.35 | 34.33 | 34.40 |
| P26 | 96.48 | 30.33 | 30.39 | 35.23 | 38.53 | 27.19 | 19.33 | 34.31 | 34.46 |
| P27 | 96.87 | 30.29 | 30.32 | 35.29 | 38.53 | 27.98 | 19.23 | 34.33 | 34.41 |
| P28 | 96.81 | 30.27 | 30.33 | 35.10 | 38.45 | 27.19 | 19.21 | 34.30 | 34.37 |
| P29 | 96.76 | 30.28 | 30.32 | 35.19 | 38.30 | 27.20 | 19.22 | 34.29 | 34.45 |

**Table 4.4** Pattern dimension of blend 3

| Dimension | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| Die dimension | 96.98 | 30.85 | 30.65 | 35.98 | 38.60 | 28.28 | 19.56 | 35.40 | 34.50 |
| P31 | 96.55 | 30.23 | 30.45 | 35.17 | 38.54 | 28.18 | 19.23 | 35.24 | 34.45 |
| P32 | 96.24 | 30.76 | 30.56 | 35.19 | 38.36 | 28.17 | 19.25 | 35.12 | 34.33 |
| P33 | 95.93 | 30.21 | 30.42 | 35.22 | 38.41 | 28.09 | 19.19 | 35.33 | 34.29 |
| P34 | 96.27 | 30.24 | 30.44 | 35.44 | 38.43 | 28.17 | 19.35 | 35.39 | 34.38 |
| P35 | 96.56 | 30.46 | 30.32 | 35.22 | 38.32 | 28.11 | 19.40 | 35.30 | 34.40 |
| P36 | 96.35 | 30.56 | 30.51 | 35.21 | 38.34 | 28.13 | 19.50 | 35.33 | 34.44 |
| P37 | 96.61 | 30.50 | 30.48 | 35.29 | 38.27 | 28.19 | 19.43 | 35.29 | 34.48 |
| P38 | 96.45 | 30.74 | 30.45 | 35.20 | 38.33 | 28.10 | 19.33 | 35.33 | 34.31 |
| P39 | 95.91 | 30.78 | 30.22 | 35.33 | 38.51 | 28.09 | 19.35 | 35.41 | 34.39 |

**Table 4.5** Pattern dimension of blend 4

| Dimension | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| Die dimensions | 96.98 | 30.85 | 30.65 | 35.98 | 38.60 | 28.28 | 19.56 | 35.40 | 34.50 |
| P41 | 96.56 | 30.57 | 30.44 | 35.68 | 38.46 | 28.19 | 19.48 | 35.24 | 34.45 |
| P42 | 96.71 | 30.59 | 30.50 | 35.60 | 38.49 | 28.10 | 19.41 | 35.30 | 34.41 |
| P43 | 96.34 | 30.44 | 30.49 | 35.38 | 38.50 | 27.98 | 19.44 | 35.31 | 34.40 |
| P44 | 96.45 | 30.72 | 30.53 | 35.47 | 38.51 | 28.09 | 19.43 | 35.30 | 34.44 |
| P45 | 96.71 | 30.45 | 30.59 | 35.49 | 38.44 | 28.12 | 19.39 | 35.29 | 34.39 |
| P46 | 96.63 | 30.76 | 30.41 | 35.51 | 38.30 | 28.19 | 19.50 | 35.29 | 34.36 |
| P47 | 96.32 | 30.70 | 30.51 | 35.54 | 38.41 | 28.20 | 19.30 | 35.31 | 34.40 |
| P48 | 96.41 | 30.66 | 30.39 | 35.59 | 38.44 | 28.19 | 19.39 | 35.36 | 34.39 |
| P49 | 96.70 | 30.61 | 30.50 | 35.61 | 38.40 | 28.17 | 19.38 | 35.29 | 34.33 |

**Table 4.6** Pattern dimension of blend 5

| Dimension | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| Die dimension | 96.98 | 30.85 | 30.65 | 34.98 | 38.60 | 28.28 | 19.56 | 35.40 | 34.50 |
| P51 | 96.80 | 30.80 | 30.55 | 34.89 | 38.46 | 28.19 | 19.45 | 35.37 | 34.28 |
| P52 | 96.82 | 30.79 | 30.58 | 34.79 | 38.48 | 28.14 | 19.48 | 35.33 | 34.41 |
| P53 | 96.79 | 30.78 | 30.49 | 34.80 | 38.50 | 28.16 | 19.40 | 35.29 | 34.38 |
| P54 | 96.90 | 30.79 | 30.47 | 34.81 | 38.49 | 28.09 | 19.39 | 35.31 | 34.40 |
| P55 | 96.89 | 30.77 | 30.50 | 34.75 | 38.51 | 28.13 | 19.41 | 35.29 | 34.41 |
| P56 | 96.88 | 30.75 | 30.55 | 34.79 | 38.48 | 28.18 | 19.43 | 35.36 | 34.44 |
| P57 | 96.90 | 30.77 | 30.58 | 34.81 | 38.33 | 28.11 | 19.44 | 35.30 | 34.40 |
| P58 | 96.87 | 30.79 | 30.51 | 34.88 | 38.39 | 28.12 | 19.50 | 35.29 | 34.33 |
| P59 | 96.88 | 30.76 | 30.53 | 34.78 | 38.48 | 28.18 | 19.49 | 35.36 | 34.38 |

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

## 4.3 Experimental work for ceramic shell

### 4.3.1 Preparation of slurry

The slurries are composed of a refractory system and a binder system. Face coat layers are constructed through dip coating. Shell mould is constructed by applying multiple dip coating, around the face coat 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 mixture for approximately 71 hours as shown in figure 4.9. Other additives are added 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, etc.

**Fig 4.9** Slurry preparation

### 4.3.2 Coating of wax pattern

The wax pattern assembly is dipped into slurry of a refractory coating material. A number of patterns are attached to a centre wax stick, or sprue, to form a casting cluster, or assembly. A wax pattern assembly is then dipped in to the primary slurry. The ceramic coating is built by dipping and stuccoing to the assembly. The purpose of stuccoing is to minimizing the drying stresses in the coating. The 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 shell built is shown in fig 4.10.

**Fig 4.10**: Coating of the wax pattern

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 calcinated coat sand up to 2 to 3 layer and16/80 mesh calcinated 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 Dewaxing and firing of mould

Solid moulds are placed in the microwave or infrared oven. First of all, the wax pattern is melted and the wax is drained from the mould. The microwave oven which melts wax is kept at a temperature of 110 $^{\circ}$C and infrared oven is kept at a temperature of 100 $^{0}$C. After removing the wax, the shell can be quickly fired at a desired temperature. Firing of mould brings full development of dry strength, eliminate traces of organic material and preheat 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 reheated moulds for pouring. Fig. 4.11 shows the pouring of 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 steel, the preheated moulds temperature should be of the order of 300 $^{\circ}$C to 500$^{0}$C and 800 $^{\circ}$C respectively. For preparing casting of non-ferrous alloy, Al-7% Si alloy was selected because of its good cast ability characteristics.

**Fig 4.11:** Metal pouring

### 4.3.5 Finishing

After solidification of the metal the ceramic mould is removed by pneumatic vibratory equipment. The casting parts are cuts from runner and after small finishing product are ready to inspection.

# CHAPTER 5
# RESULTS AND DISCUSSION

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

## 5.1 STANDRIZATION OF WAX PROPORTION

The wax pattern deformation is very important in predicting tooling allowances. The wax proportion should be such that gives minimum shrinkages of the wax. The average linear shrinkage of pattern dimension, volumetric shrinkage, surface roughness and hardness are calculated from the measured data. The results indicate that the change of the pattern from the liquid to solid state is accompanied by volume contraction. The results obtained by using the Taguchi design of experiments are summarized in the table 5.1. The average properties of the wax blends are shown in table 5.2. After conducting the experiments it is observed that wax blend 4 gives minimum linear shrinkage, volumetric shrinkage and surface roughness and maximum hardness as shown in table 5.3.

**Table 5.1** Experimental data of wax blends

| Expt. No. | Process Variable | | | | Measured Properties | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | Blend 1 | | | | Blend 2 | | | | Blend 3 | | | | Blend 4 | | | | Blend 5 | | | |
| | | | | | %LS | %VS | %SR | %H | %LS | %VS | %SR | %H | %LS | %VS | %SR | %H | %LS | %VS | %SR | %H | %LS | %VS | %SR | %H |
| 1 | 65 | 44 | 440 | 8 | 1.83 | 4.53 | 1.25 | 2.5 | 1.41 | 8.88 | 1.50 | 3 | 1.18 | 5.15 | 1.29 | 3 | 0.60 | 3.02 | 0.81 | 3.8 | 1.78 | 4.98 | 1.98 | 3.1 |
| 2 | 65 | 46 | 490 | 10 | 1.77 | 4.32 | 1.31 | 1.5 | 2.79 | 8.17 | 1.89 | 2.5 | 1.29 | 5.07 | 1.09 | 2.4 | 0.75 | 2.58 | 0.86 | 2 | 1.71 | 5.08 | 1.82 | 3 |
| 3 | 65 | 48 | 540 | 12 | 1.57 | 4.53 | 1.62 | 2 | 2.78 | 9.64 | 1.69 | 2 | 1.42 | 4.99 | 1.21 | 2 | 0.67 | 2.47 | 0.79 | 2.5 | 1.81 | 5.37 | 1.76 | 2 |
| 4 | 70 | 44 | 490 | 12 | 1.79 | 4.47 | 1.77 | 2.5 | 2.63 | 8.99 | 1.65 | 1.5 | 1.25 | 5.23 | 1.38 | 2.5 | 0.63 | 2.51 | 0.82 | 3.8 | 1.82 | 4.76 | 1.77 | 1.9 |
| 5 | 70 | 46 | 540 | 8 | 2.47 | 4.41 | 1.26 | 1 | 2.90 | 9.12 | 1.76 | 2 | 1.33 | 5.19 | 1.14 | 3 | 0.68 | 2.55 | 0.89 | 3 | 1.79 | 5.01 | 1.69 | 2 |
| 6 | 70 | 48 | 440 | 10 | 1.00 | 4.58 | 1.41 | 1.2 | 2.47 | 8.78 | 1.71 | 3 | 1.43 | 5.21 | 1.29 | 2.5 | 0.70 | 2.75 | 0.75 | 2.9 | 1.82 | 5.32 | 1.90 | 2.5 |
| 7 | 75 | 44 | 540 | 10 | 1.75 | 4.40 | 1.20 | 1.5 | 2.37 | 9.65 | 1.64 | 2.5 | 1.37 | 5.16 | 1.20 | 2 | 0.81 | 2.61 | 0.77 | 3.5 | 1.69 | 5.23 | 1.88 | 3 |
| 8 | 75 | 46 | 440 | 12 | 1.50 | 4.44 | 1.78 | 1 | 2.54 | 8.88 | 1.75 | 1 | 1.40 | 5.19 | 1.23 | 1.9 | 0.78 | 2.51 | .076 | 2.8 | 1.73 | 5.23 | 1.86 | 3.2 |
| 9 | 75 | 48 | 490 | 8 | 1.30 | 4.47 | 1.30 | 1.3 | 2.47 | 8.56 | 1.73 | 1.5 | 1.58 | 5.20 | 1.19 | 2 | 0.69 | 2.34 | 0.81 | 3 | 1.86 | 5.44 | 1.59 | 3 |
| Average | | | | | 1.58 | 4.46 | 1.43 | 1.61 | 2.48 | 8.96 | 1.70 | 2.11 | 1.36 | 5.15 | 1.22 | 2.36 | 0.701 | 2.59 | 0.806 | 3.03 | 1.77 | 5.17 | 1.80 | 2.63 |

A=Injection temperature ($^{o}$C) B=Die temperature ($^{o}$C) C=Injection force (N) D=Holding time (min.)

%LS=% Linear Shrinkage %VS=%Volumetric Shrinkage %SR=Surface Roughness %H=%Hardness

The average of wax blends 5 with its properties are shown in table no. 5.2.

**Table 5.2** Properties of wax blends

| Blend No. | Average linear shrinkage (%) | Average volumetric shrinkage (%) | Average surface roughness(μm) | Hardness |
|---|---|---|---|---|
| 1 | 1.58 | 4.46 | 1.43 | 1.61 |
| 2 | 2.48 | 8.96 | 1.70 | 2.11 |
| 3 | 1.36 | 5.15 | 1.22 | 2.36 |
| 4 | 0.701 | 2.59 | 0.806 | 3.03 |
| 5 | 1.77 | 5.17 | 1.80 | 2.63 |

The change in properties of wax blend 4 are shown in table 5.3.

**Table 5.3** Experimental data of wax blend 4

| Expt. No. | Process Variable | | | | Measured Properties | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | Blend 4 | | | |
| | | | | | %LS | %VS | %SR | %H |
| 1 | 65 | 44 | 440 | 8 | 0.60 | 3.02 | 0.81 | 3.8 |
| 2 | 65 | 46 | 490 | 10 | 0.75 | 2.58 | 0.86 | 2 |
| 3 | 65 | 48 | 540 | 12 | 0.67 | 2.47 | 0.79 | 2.5 |
| 4 | 70 | 44 | 490 | 12 | 0.63 | 2.51 | 0.82 | 3.8 |
| 5 | 70 | 46 | 540 | 8 | 0.68 | 2.55 | 0.89 | 3 |
| 6 | 70 | 48 | 440 | 10 | 0.70 | 2.75 | 0.75 | 2.9 |
| 7 | 75 | 44 | 540 | 10 | 0.81 | 2.61 | 0.77 | 3.5 |
| 8 | 75 | 46 | 440 | 12 | 0.78 | 2.51 | 0.76 | 2.8 |
| 9 | 75 | 48 | 490 | 8 | 0.69 | 2.34 | 0.81 | 3 |
| Average | | | | | 0.701 | 2.59 | .806 | 3.03 |

The change in properties of wax blends are shown in the bar charts (Fig 5.1 to 5.4).

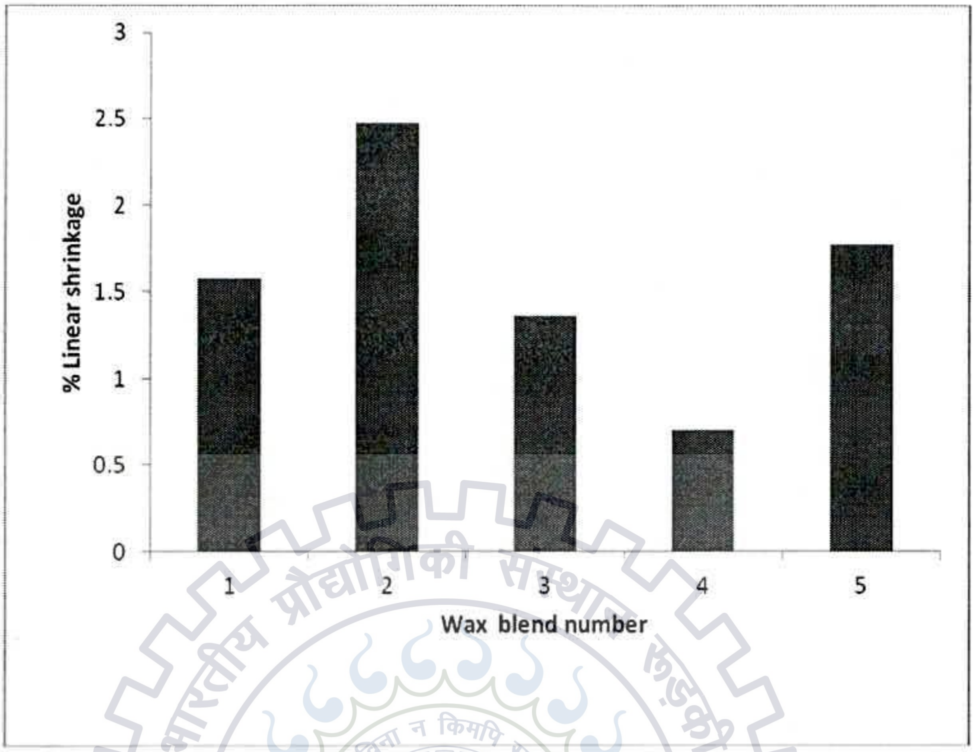

**Fig 5.1** Linear shrinkage of wax blends

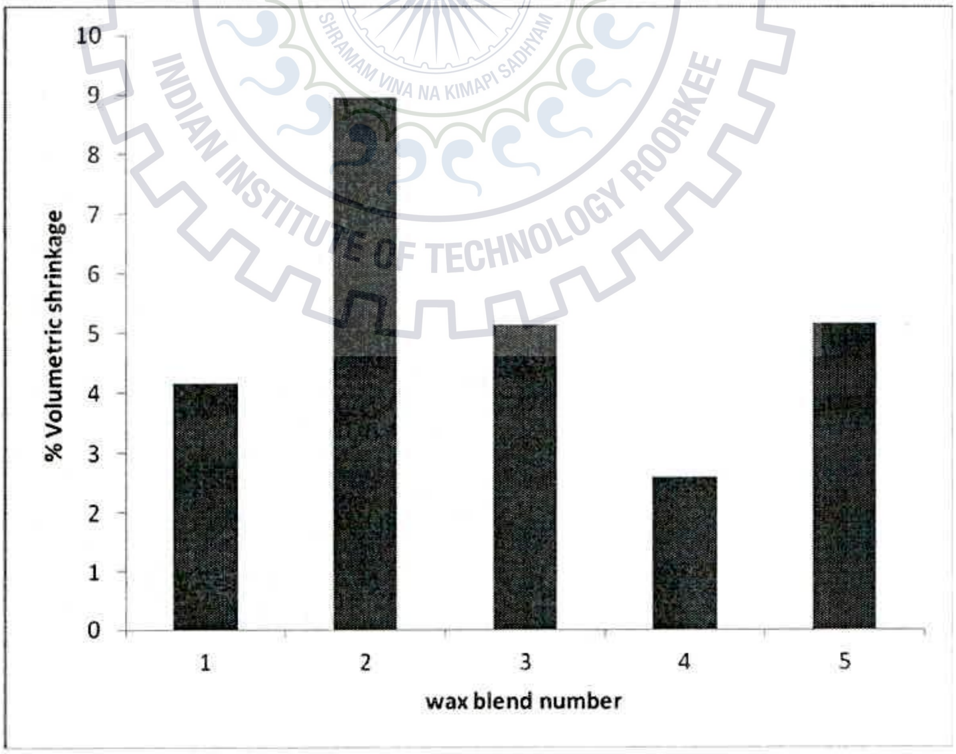

**Fig 5.2** Volumetric shrinkage of wax blends

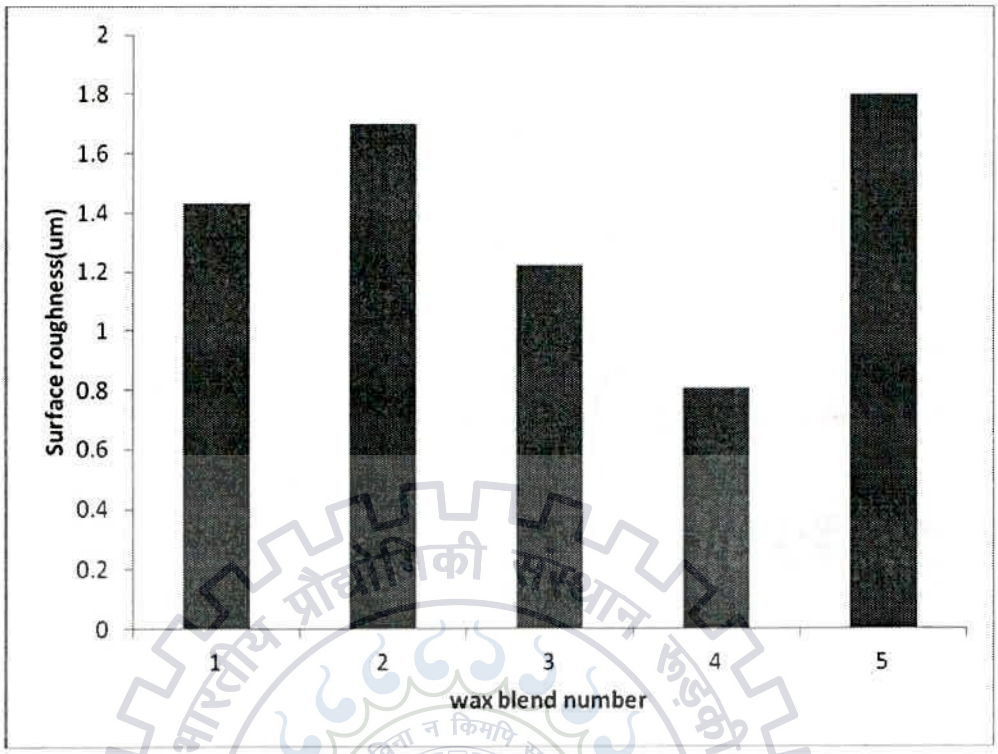

**Fig 5.3** Surface roughness of wax blends

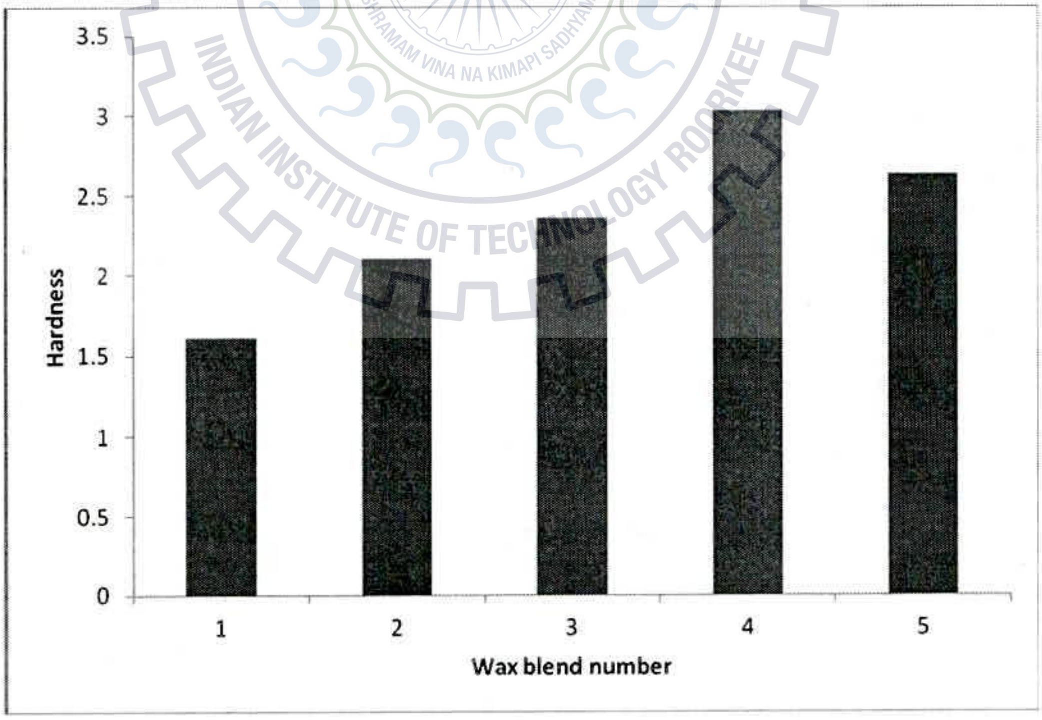

**Fig 5.4** Hardness of wax blends

## 5.2 EFFECTS OF PROCESS PARAMETERS ON THE LINEAR SHRINKAGE

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

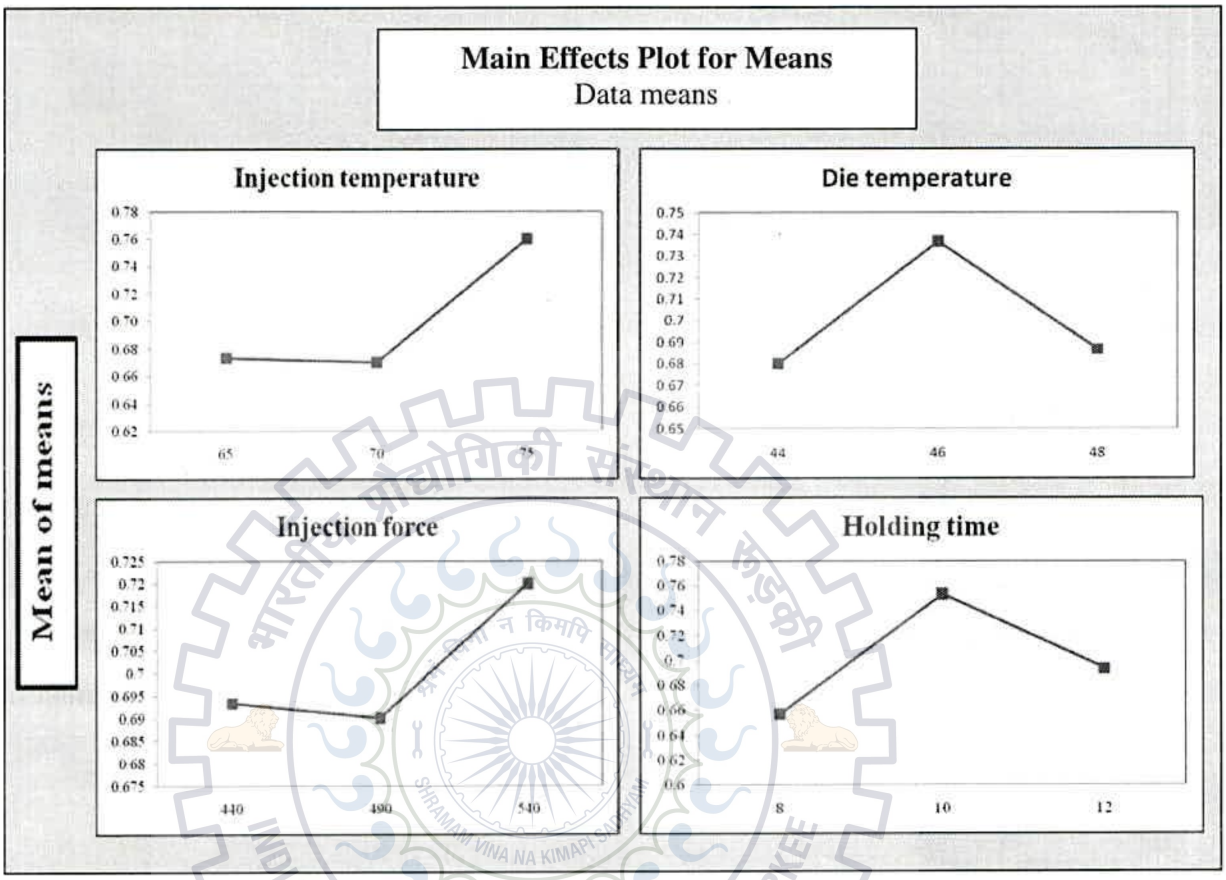

**Fig 5.5** Effects of process parameters on linear shrinkage

It is observed from the figure 5.5 that the % linear of linear shrinkage decreases as the injection temperature increase and is minimum at 70 $^0$C. Linear shrinkage is increasing as the injection temperature increasing. It is due to high injection temperature results in evaporation of volatile content, some loss of material from wax blend.

As the die temperature increases linear shrinkage increases this may be due to the reason that with an increase in injection temperature and die temperature an even temperature field does not exists which causes the wax blend to cool non uniformly and results in more shrinkage and is maximum at 46$^0$C. But further decrease in die temperature with an increase in injection temperature decrease the linear shrinkage. The injection force to inject the wax blend into the die increases the linear shrinkage decrease. Injection force increases the linear shrinkage increase.

The holding time after inject the wax blend in to the die increase the linear shrinkage increases.

## 5.3 EFFECTS OF PROCESS PARAMETERS ON VOLUMETRIC SHRINKAGE

The effects of process parameters on volumetric shrinkage are shown in the following graph (figure 5.6)

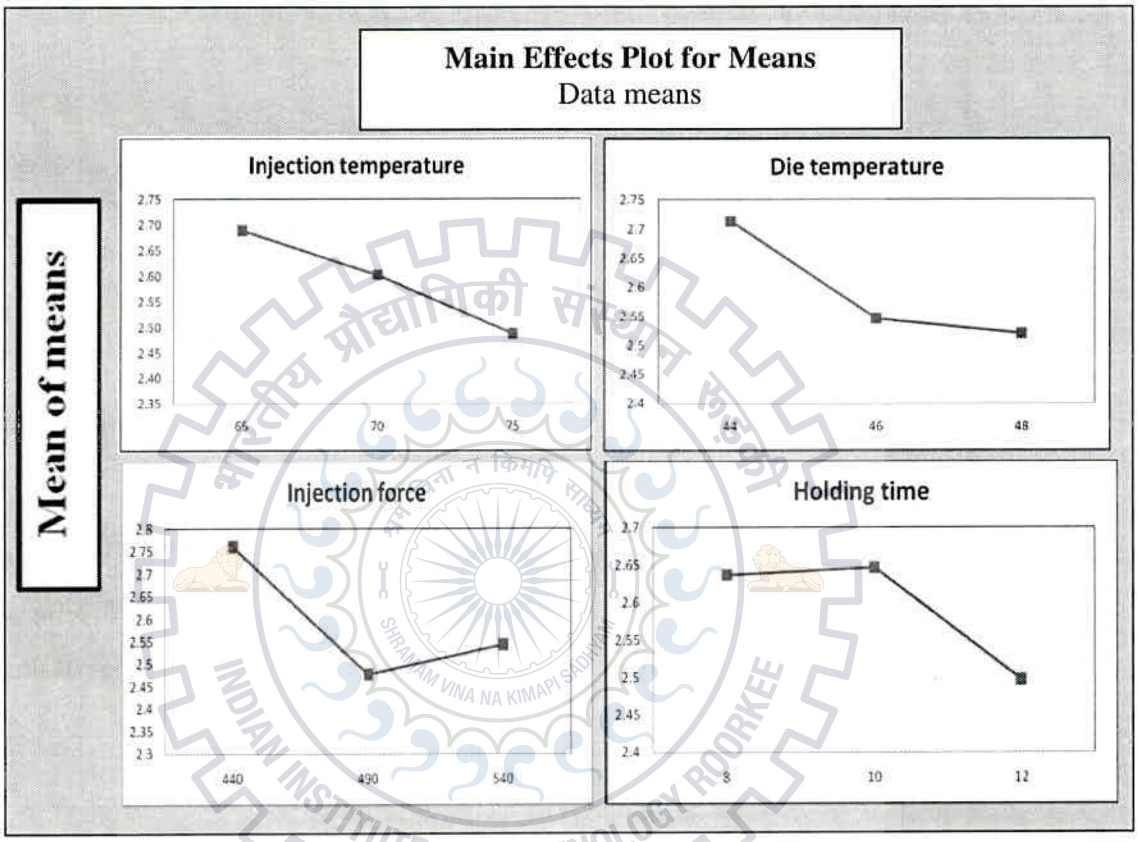

**Fig 5.6** Effects of process parameters on volumetric shrinkage

It is observed from the figure 5.6 that the % of volumetric shrinkage decrease as the injection temperature increase and is minimum at 75 $^0$C. The die temperature increase volumetric shrinkage decreases this is may 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 48 $^0$C. But Injection force and the holding time have the positive effect on the volumetric shrinkage. As the injection force and holding time to inject the wax blend in to the die increase the volumetric shrinkage decrease.

## 5.4 EFFECTS OF PROCESS PARAMETERS ON THE SURFACE ROUGHNESS

The effects of process parameters on the surface roughness are shown in the following graph (figure 5.7). It observed from the figure that increase in injection temperature and die temperature reduce the surface roughness which is minimum at 75 $^0$C and 48 $^0$C. This is due to better replication of the mould surface.

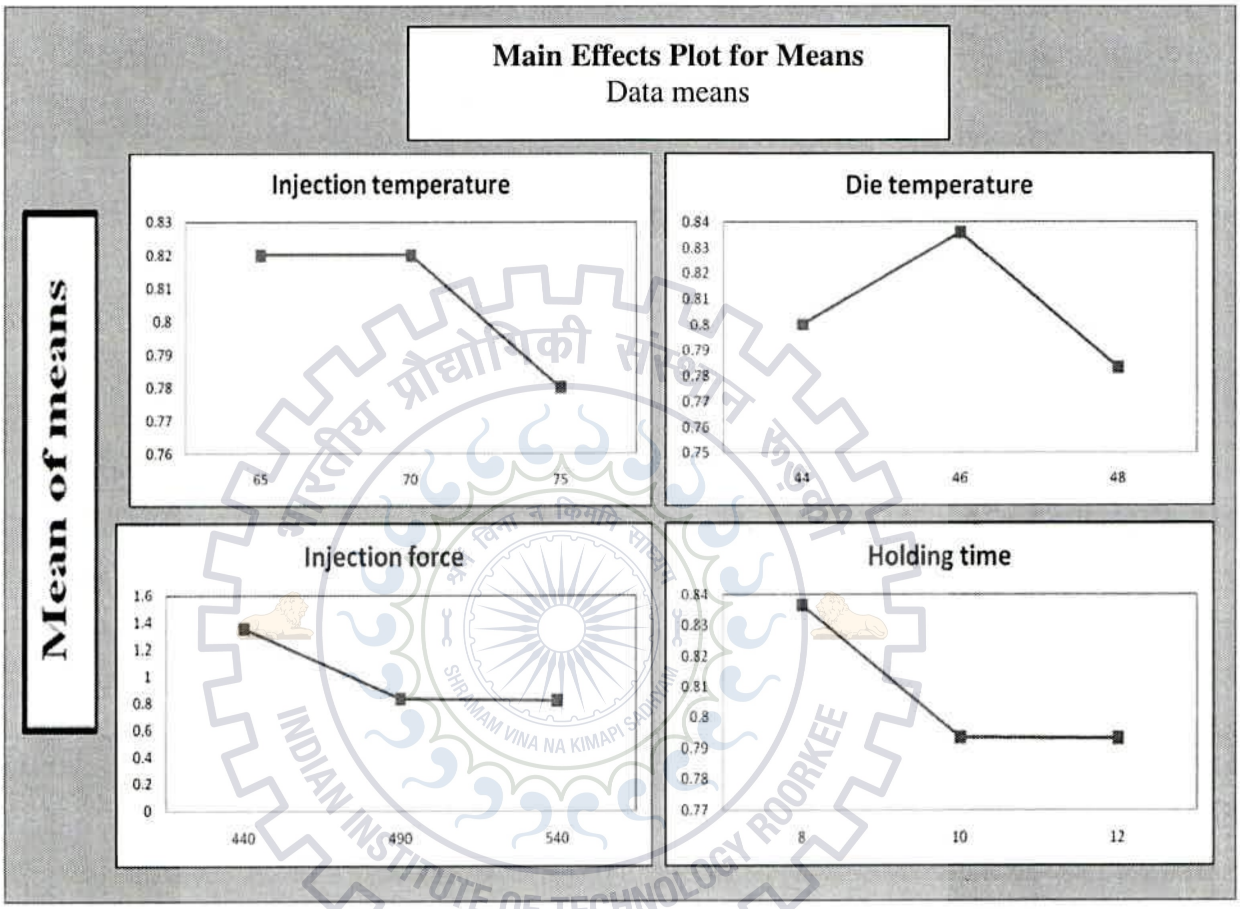

**Fig 5.7:** Effects of process parameters on surface roughness

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

## 5.5 EFFECTS OF PROCESS PARAMETERS ON THE HARDNESS

The effects of process parameters on the hardness are shown in the following graph (fig 5.8). It is observed from the figure that the hardness is increasing with increasing in injection temperature and it is minimum at 75 $^0$C. With the increase in die temperature the volumetric shrinkage is decreasing and it is minimum at 46 $^0$C.

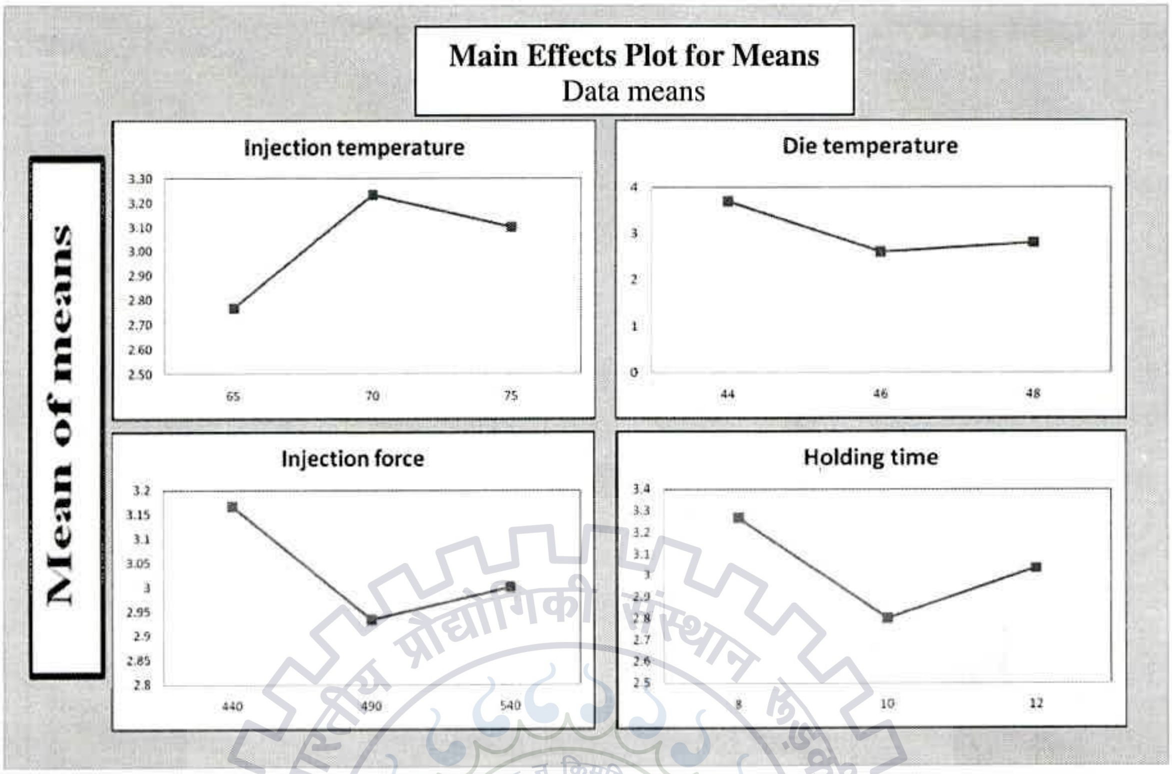

**Fig 5.8:** Effects of process parameters on hardness

The hardness is decreasing with increasing in injection force and minimum at 490 N. The hardness is increasing with increase in holding time.

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

- Injection temperature: 75 $^0$C
- Die temperature: 48$^0$C
- Injection force: 490 N
- Holding time: 12 minutes

## 5.6 CHANGES IN PROPERTIES OF WAX AFTER DEWAXING OF SHELL IN MICROWAVEN OVEN

We are using domestic type of microwave oven for dewaxing of wax pattern. The wax model is placed inside a domestic type of microwave oven which is operating under a frequency of 2.45 GHz, a power of 1100 W, for a period of 15 min at room temperature and pressure of 1 atm, reaching a maximum temperature of 110 ° C .The main advantage of dewaxing by using microwave is that no purification treatment is required on the resulting wax. Dewaxing by using microwave was repeated up to 9 cycles.

According to the above experimental data blend 4 is giving best result .So the further experiment is done by using blend 4. The compositions of waxes are in table 5.4.

**Table 5.4:** composition of wax

| NAME OF THE WAX | % OF THE WAX (GM) |
|---|---|
| Paraffin wax | 60 |
| Carnauba wax | 20 |
| Microcrystalline wax | 20 |

Experimental data of change in properties of wax after repeated cycles while dewaxing is done in microwave oven is given in table 5.5

**Table 5.5** Change in properties after dewaxing in microwave oven

| NO. OF CYCLES | PROCESS VARIABLE | | | | MEASURED PROPERTIES | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Blend 4 | | | |
| | A | B | C | D | %LS | %VS | %SR | %H |
| 1 | 75 | 48 | 490 | 12 | 0.5 | 1.5 | 0.4 | 1.5 |
| 2 | 75 | 48 | 490 | 12 | 0.8 | 2 | 0.7 | 2 |
| 3 | 75 | 48 | 490 | 12 | 1.3 | 3.5 | 1.0 | 1.7 |
| 4 | 75 | 48 | 490 | 12 | 1.5 | 4.1 | 1.4 | 1.5 |
| 5 | 75 | 48 | 490 | 12 | 1.6 | 4.9 | 1.8 | 2.5 |
| 6 | 75 | 48 | 490 | 12 | 1.9 | 5.3 | 2.0 | 2 |
| 7 | 75 | 48 | 490 | 12 | 2.3 | 6.1 | 2.4 | 2.5 |
| 8 | 75 | 48 | 490 | 12 | 2.5 | 6.9 | 2.9 | 2 |
| 9 | 75 | 48 | 490 | 12 | 2.8 | 7.8 | 3.0 | 1.9 |
| Average | | | | | 1.68 | 4.67 | 1.73 | 2.17 |

The change in properties of wax blends are shown in the bar charts (Fig.5.9 to 5.12).

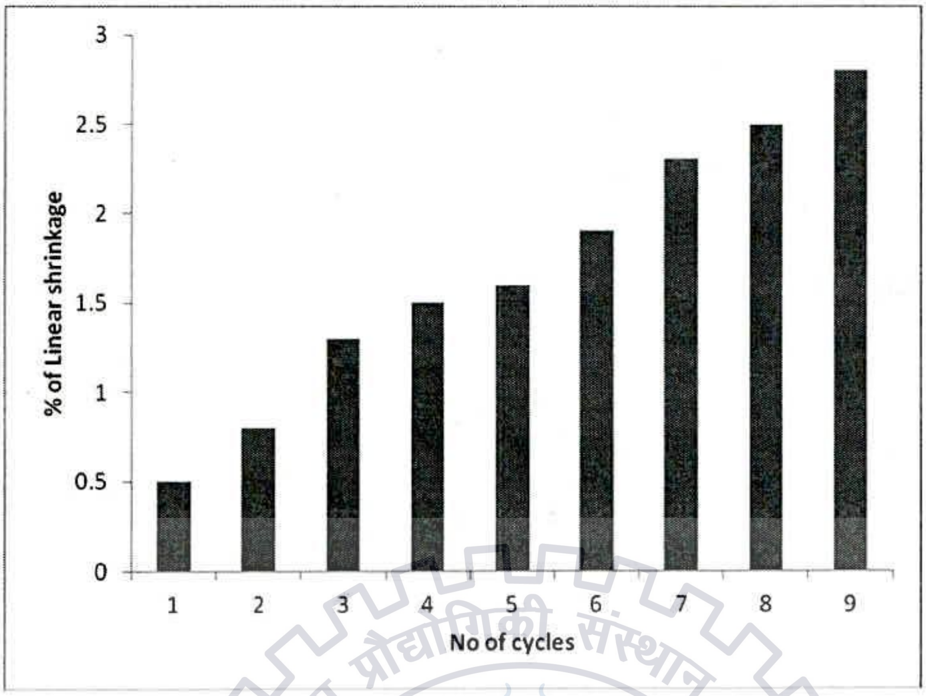

**Fig 5.9:** Linear shrinkage of wax blends

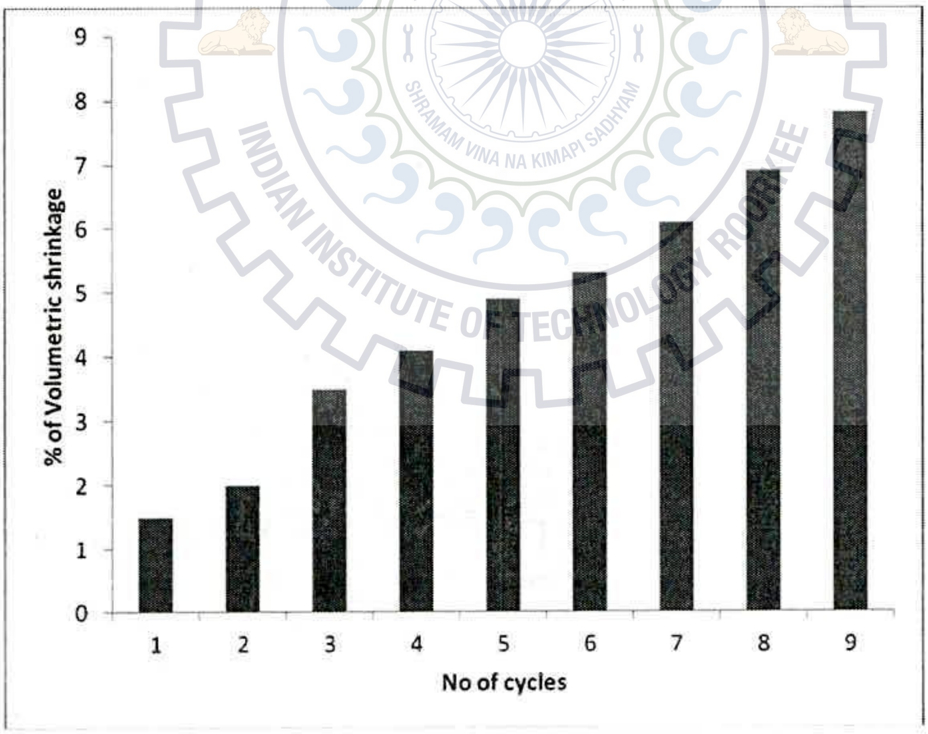

**Fig 5.10:** Volumetric shrinkage of wax blends

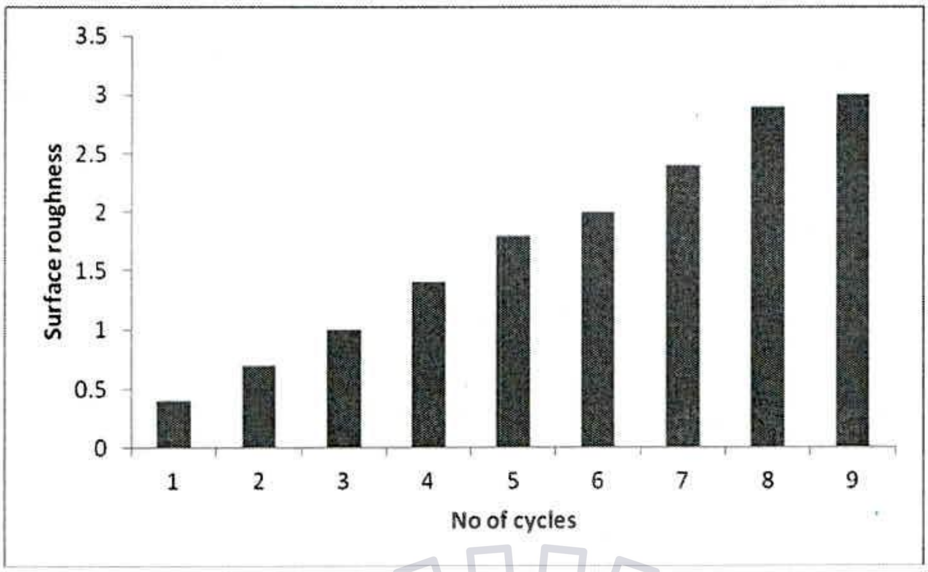

**Fig 5.11** Surface roughness of wax blends

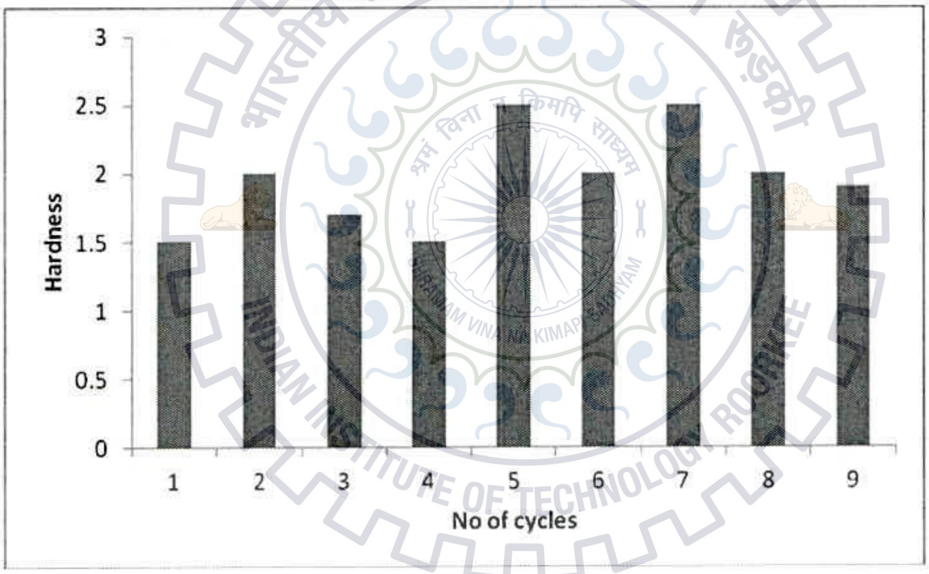

**Fig 5.12** Hardness of wax blends

## 5.7 CHANGES IN PROPERTIES OF WAX AFTER DEWAXING OF SHELL IN INFRARED OVEN

In infrared oven, there are 4 bulbs of 250 watts to produce the thermal effect for dewaxing the blend at the constant temperature. The frequency of infrared oven is 215 THz. For dewaxing, the blend is placed in hanger and a vessel is placed below the hanger, so that melted wax is dropped slowly into the vessel. The time taken for total dewaxing is 30 min. The stored melted wax is used again and again for recycling purposes up to 9 times. The change in properties after dewaxing in infrared oven is shown in table 5.6.

**Table 5.6** Change in properties after dewaxing in infrared oven

| NO. OF CYCLES | PROCESS VARIABLE | | | | MEASURED PROPERTIES | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | Blend 4 | | | |
| | | | | | %LS | %VS | %SR | %H |
| 1 | 75 | 48 | 490 | 12 | 0.7 | 1.9 | 0.6 | 2.0 |
| 2 | 75 | 48 | 490 | 12 | 1.3 | 2.3 | 0.9 | 1.5 |
| 3 | 75 | 48 | 490 | 12 | 1.9 | 2.8 | 1.2 | 2.5 |
| 4 | 75 | 48 | 490 | 12 | 2.1 | 3.2 | 1.6 | 2.5 |
| 5 | 75 | 48 | 490 | 12 | 2.7 | 3.7 | 1.9 | 3 |
| 6 | 75 | 48 | 490 | 12 | 3 | 4.0 | 2.3 | 1.5 |
| 7 | 75 | 48 | 490 | 12 | 3.2 | 4.3 | 2.7 | 2.5 |
| 8 | 75 | 48 | 490 | 12 | 3.6 | 4.8 | 3.0 | 2.7 |
| 9 | 75 | 48 | 490 | 12 | 3.9 | 5.1 | 3.5 | 2.5 |
| Average | | | | | 2.48 | 3.56 | 1.96 | 2.8 |

The % of linear shrinkage, volumetric shrinkage, surface roughness and hardness are shown in bar charts (Fig. 5.13 to 5.16).

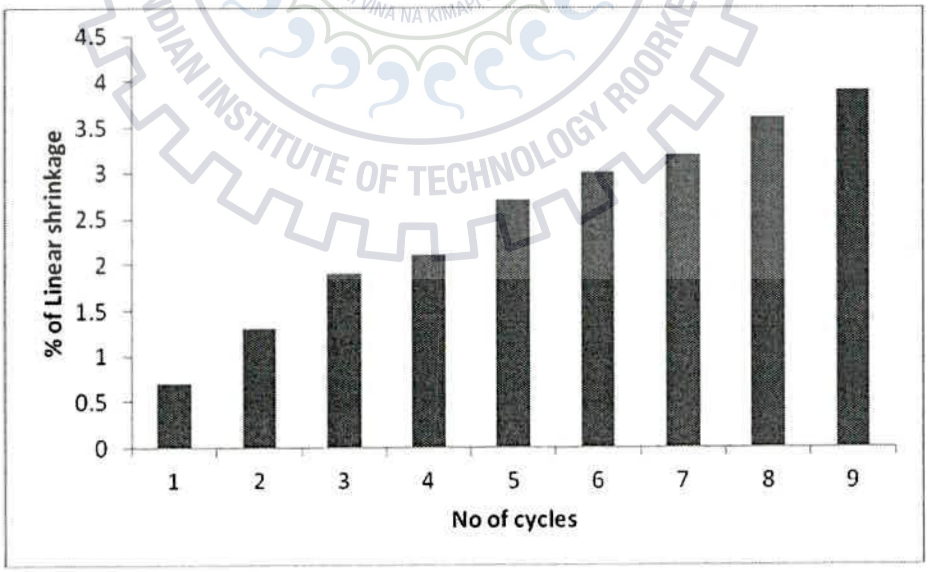

**Fig 5.13** Linear shrinkage of wax blends

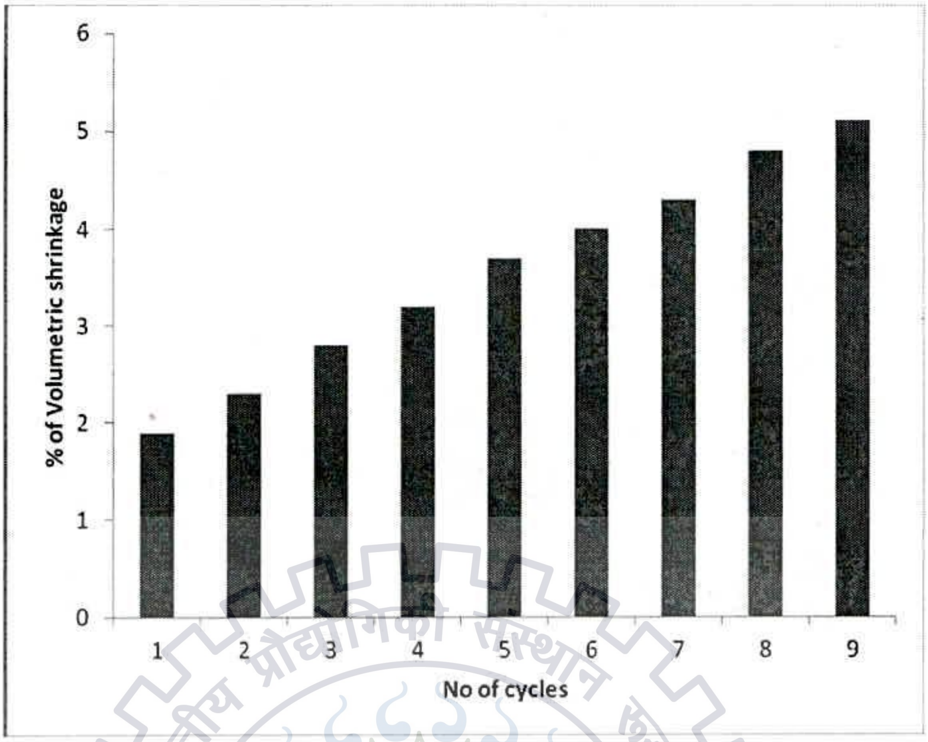

**Fig 5.14** Volumetric shrinkage of wax blends

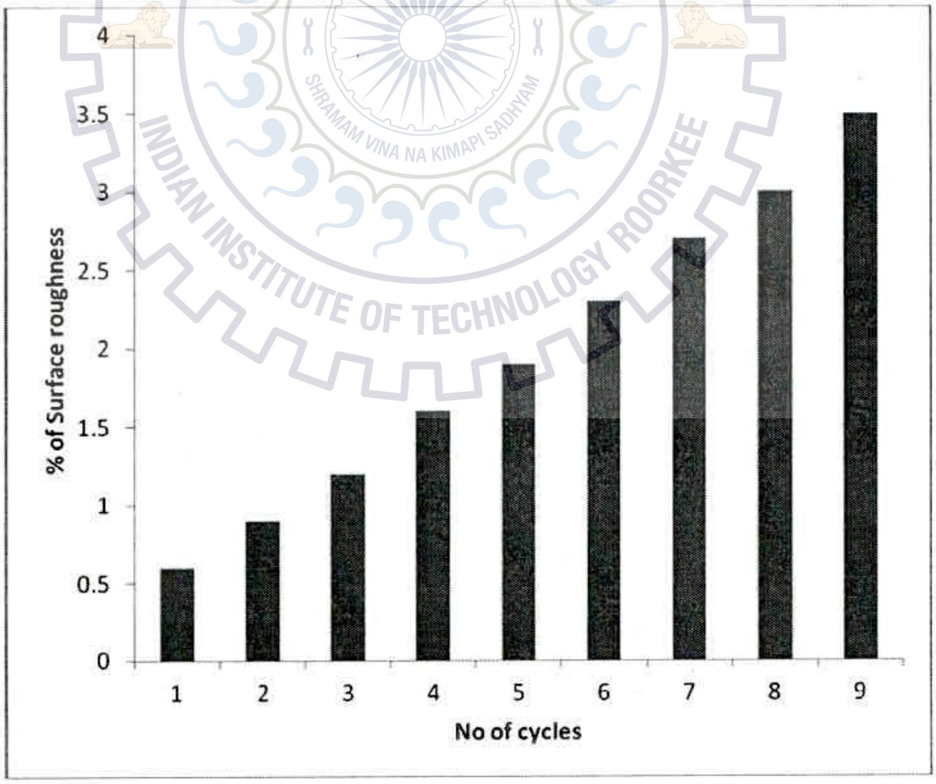

**Fig 5.15** Surface roughness of wax blends

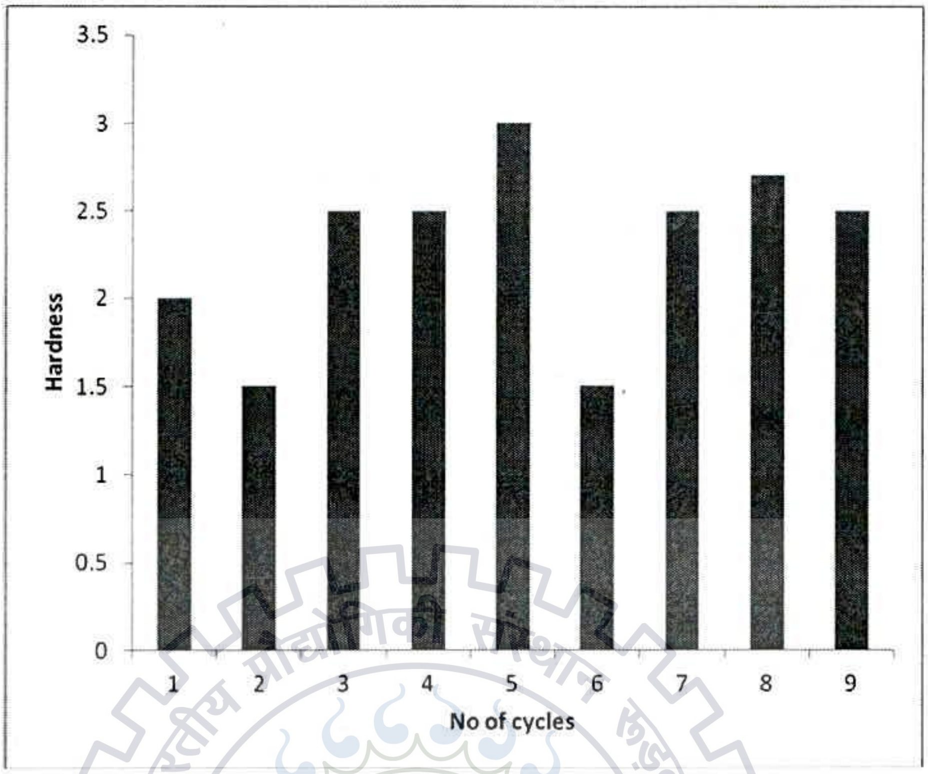

**Fig 5.16** Hardness of wax blends

# CHAPTER 6

# CONCLUSIONS AND SCOPE FOR FUTURE WORK

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

## 6.1 CONCLUSIONS

The conclusions from the present work are listed below.

1. Wax blend compositions significantly affect the shrinkage, dimensional accuracy, surface roughness and hardness of the patterns after repeated dewaxing cycles.
2. The wax blend 4 with proportion of paraffin wax 60%, carnauba wax 20% and microcrystalline 20% wax gives the better result to minimize to volumetric shrinkage, linear shrinkage, as well as surface roughness and maximize hardness of the pattern.
3. It is possible to enhance dimensional accuracy, shrinkage and surface finish of wax patterns effectively, by controlling wax injection variables.
4. The optimum process parameters which gives the minimum shrinkage and surface roughness and good hardness of wax pattern are as follows:
   - i. Injection temperature: $75^{0}$C
   - ii. Die temperature: $48^{0}$C
   - iii. Injection force: 490N
   - iv. Holding time: 12 minutes
5. The following optimal values (24) for best coating mixture slurry are as:
   - i. Zircon flour: 450 gm
   - ii. Fused silica: 300 gm
   - iii. Refractory/Binder ratio: 2.5
   - iv. Catalyst: 3 ml
   - v. Viscosity: 2075 cp
   - vi. Density: 2.38 gm/ml
   - vii. Surface roughness: 2.35μm.

6. The main advantage of microwave and infrared dewaxing as compared to conventional dewaxing in furnace, boiler clave etc is that resulting wax does not require any purification. Microwave and infrared dewaxing is environmental friendly.

7. The dewaxing of wax from ceramic shell is done in domestic microwave oven operating under a frequency of 2.45 GHz, a power of 1100W and for a 15-min period at room pressure (1atm), reaching a maximum temperature of $110^{o}$C. It takes less time as compared to infrared oven operating under frequency of 215 THz. The time of placing blend in infrared oven is 30 min and maximum temperature is $100^{0}$ C.

## 6.2 SCOPE FOR FUTURE WORK

The following recommendations are made for future work.

1. Higher order Orthogonal Array (OA) can be considered to incorporate all the possible interactions of the process parameters.
2. Genetic algorithms can be used for the optimization of responses.
3. Some techniques should be developed to maintain desired coating thickness and permeability of ceramic shell.
4. Numerical simulations are required to understand the process and to minimize the time and cost associated in investment casting.

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1. Doli Rani and D.B. Karunakar, "Influence of microwave dewaxing on the wax properties in investment casting process", Proceedings of National Conference on Advances in Manufacturing Technology, May 23-24, 2013, NITTR, Chandigarh.

2. Doli Rani and D.B. Karunakar, "Recycling of pattern wax in the investment casting process using microwave dewaxing" IOSR Journal of Engineering, Vol. 3, Issue 5 (May. 2013), Vol. 2, pp 05-10.