A Study on Blended Wax Pattern in Investment Casting Process

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ABSTRACT

Investment casting is known for its ability to produce components of excellent surface finish, dimensional accuracy and complex shapes. Inadequate surface finish, hardness and excessive shrinkage of the wax pattern often result in poor quality of the finished casting. Hence, in the present study, an attempt has been made to produce a wax blend which could offer better surface finish, minimum shrinkage and moderate hardness. Experiments were conducted with different types of waxes namely Paraffin wax, Bees wax, Montan wax and Carnabua wax, varying their proportions and stirring time. In each case, properties of wax pattern like surface finish, percentage shrinkage and hardness were determined. An attempt was made to find out the set of input parameters, which could offer a set of ideal properties of the wax blend, using Taguchi method. The set of input parameters suggested by Taguchi method was experimentally verified and found to offer the set of desired optimal properties of the wax blend pattern.

1.1 INVESTMENT CASTING (LOST WAX CASTING)

The name lost wax is the most common name for this process and comes from the wax lost informing the cavity. Investment is the name given to the refractory material used to form the mould. Both names are correct but lost wax is the older traditional name and investment casting is the modern technical one. Bronze and precious metal objects have been produced by this method for at least 6000 yrs.Craftsman in China, India, Persia, Greece, Egypt, Italy and many other areas produced workranging from small items of jewellery to large statues using this process.

One of the most famous lost wax castings of the Renaissance period are four doors in the church of San Giovanni (St John the Baptist) in Florence, Italy. The timber doors with high relief panels were made by Lorenzo Ghiberti starting about the year 1380. One pair of doors has ten panels and the other pair has twenty eight panels. Each door is five meters high and weighs severaltonnes. The panels are cast in bronze and took 48 years to complete.

In recent years woodwind manufacturers have started to use this process to produce KEYWORK instead of the traditional power forging. The initial low cost of patterns together with the low finishing costs have made this process attractive for small and medium volume production.The lost wax casting process offers several advantages over other casting processes such assand casting, shell moulding and die-casting. It can also be used to reduce assembly and finishing times and therefore, costs..

Investment casting (also known as ‘lost wax casting’ or ‘precision casting’) has been the most widely used process for several centuries. In this casting technique, a pattern, usually made of wax, is utilized in forming the inside cavity of a refractory mold. The pattern is formed by injecting themolten wax into a permanent mold of the desired shape and there by cooling it until solidification. In the ceramic shell method, the pattern or a cluster of such patterns is yare gated to a wax sprue. Then the sprued pattern or patterns are invested with ceramic slurry which is then solidifiedforming a mold around the wax pattern. The wax pattern is then removed from the mold by melting or burning.

1.2 STRUCTURE OF INVESTMENT CASTING WAX

Modern blends of investment casting wax are complex compounds containing numerous components such as natural hydrocarbon wax, natural ester wax, synthetic wax, natural and synthetic resins, organic filler materials and water. Many variations of such compounds have been formulated to suit various requirements; properties such as melting point, hardness, viscosity, expansion and contraction, setting rate etc are of course all influenced by the structure and composition of any wax compound. Hydrocarbon wax, natural ester wax, synthetic waxes and some resins are aliphatic compounds (straight chained carbon atoms). However, some of the resins and filler materials are of ring structured carbon atoms (aromatic compounds). The short chain wax compounds have lower melting point and low hardness. With increasing chain length both hardness and melting or congealing point rise. The chain length will also influence viscosity and solubility of the wax. The casting wax is a mixture of a large number of compounds of different chain lengths resulting in physical properties different from other substances. Wax does not melt immediately on heating like other homogeneous chemical compounds, but passes through an intermediate state. With gradual heating, solid wax first becomes softer, then plastic and then semi plastic. At higher temperature it acquires the consistency of a semi liquid and finally to a Newtonian liquid. It should be noted here that filled wax is not a true Newtonian liquid. This change in state occurs as short chain fractions melt first while longer chains remain solid. With further increase in temperature the latter melt progressively until the liquid state is reached. Structure or components of casting wax will also affect expansion and contraction. Wax expands like other materials under the influence of heat and on cooling it contracts. In comparison with a metal the expansion of a wax is relatively high. In this brief look at structure we have a simplified view of how or why numerous components are added to a wax blend and the properties that result. We can now consider the types of investment casting available and how these are categorized.

1.3 CATERGORISATION OF INVESTMENT CASTING WAX

Investment casting wax is broadly classified as shown • Pattern wax • Reclaim or reconstituted wax • Water soluble wax • Other special wax – including dipping, patching and adhesive. Pattern wax can be further divided into the following three main areas: • Straight or unfilled pattern wax • Emulsified pattern wax • Filled pattern wax Unfilled pattern wax is a complex compound of many waxes and resin components. The surface finish is glossy and the wax can be reclaimed and reconstituted for use. Emulsified pattern wax is similar to unfilled wax compounds, but is emulsified with 7-12% water. The surface finish is smooth and the water acts partially as a filler. This wax can be reclaimed and reconstituted for use. Filled pattern wax again is similar to unfilled wax compounds, but is blended with a powdered, inert filler material, insoluble in the base wax, to give the compound greater stability and less cavitation. It is essential that the filler used is organic to ensure complete burnout leaving no ash and there are a number of different filler materials used. It is also critical to use fine particle sized filler so that surface finish is not impaired and to have the specific gravity of the filler as near as possible to the base wax to ensure minimum separation takes place when the wax is liquid. Here again filled wax is widely used and with advance reclaim technology can usually be reclaimed and reconstituted for use. Reclaim or reconstituted wax is a service carried out by the wax manufacturer, whereby a foundry's used wax can be thoroughly cleaned and blended or reconstituted to an agreed specification. The material is then returned for use on runner systems or patterns again. Unfilled wax, emulsified wax and filled wax can all be reclaimed and reconstituted in this way. Water soluble wax is designed to produce internal shapes which are difficult to produce by other means. The wax is soluble in water or a mildly acidic solution. Other special wax grades are unfilled wax compounds used in dipping, patching or repair and adhesive applications. We now move on to look at how the general properties of investment casting wax influence quality.

1.4 PROPERTIES OF INVESTMENT CASTING WAX AND THEIR INFLUENCE ON QUALITY

Investment casting wax materials are blend of numerous complex compounds. Each compound has been included to influence the final properties of the wax in some way. A few points that affect the quality of a casting wax and hence pattern production are listed. 1. Contraction and cavitation: Stable results on contraction and cavitations of a casting wax are extremely important to the foundry. We have already discussed how structure and composition affects contraction. This highlights the importance of both the wax manufacturer and foundry's quality control tests. 2. Congealing point or melting point: Congealing point and melting point are temperatures at the beginning and end of the semi-liquid state respectively. They have a major influence on the injection temperature & pressure settings of the injection machine. 3. Ash content: Most foundries would be aware of the importance of using and maintaining wax with low ash content and of the detrimental effect of ash. The limit generally recommended is 0.05% maximum. 4. Hardness and elasticity: Casting wax must have sufficient hardness and elasticity to help reduce the possibility of rejects due to breakages, bending or other undesirable phenomena during the subsequent processing of the wax pattern. 5. Viscosity: The viscosity of a casting wax compound is critical to successful pattern production. Where large fine sections need to be produced then often a low viscosity wax is required to enable the wax to penetrate into the finest spaces in the die. For heavier sections a less fluid wax may be preferred. Viscosity is generally directly related to injection temperature. 6. Good surface finish: A good surface finish is an important property for successful pattern production. In general, unfilled wax has a glossy surface, emulsified wax has more surface smoothness, whereas filled wax has a slightly rough surface. Surfaces that could prove detrimental, are the ‘soft easily damaged’ surface or the ‘pitted’ surface usually associated with coarse particle sized filler being used. 7. Setting rate: On one extreme, some production parts require a very fast set and release from the die, whereas on the other extreme a slower setting wax is an advantage. 8. Oxidation stability: Oxidation or breakdown of certain compounds in wax due to the action of heat or simply ageing will markedly change the overall properties and the wax may become unsuitable for use. It is necessary for the manufacturer to use antioxidant materials where this could occur and foundries must be aware of this. 9. Reclaimibility: The Reclaimibility of wax are important economic and ecological issues. While stating it is possible to reclaim and reconstitute all three categories of wax, strict quality control over the process is recommended. The above points considered should cover the majority of properties of an investment casting wax and how these can affect quality of wax and wax pattern production.

1.5 WAX PATTERN PRODUCTION AND THE MONITORING OF FAULTS

If problems with wax pattern production are being encountered, it is very important to consider with the wax supplier a number of fault guidelines. The most common faults encountered during wax injection are: 1. Flow lines: are usually associated with; a) Cold die b) Cold wax c) Incorrect injection pressure d) Injecting a thick section through a thin section 2. Trapped air: is usually associated with; a) Wax too hot – causing turbulence during injection b) Flow rate too high – the wax flowing into the die faster than the air escaping through the joints, thus becoming trapped. c) Air entrapped in the wax in the machine, causing air bubbles to be injected with wax. d) Air trapped in the patching wax when filling in slots in ceramic cores. 3. Lubricant marks: can be associated with over – lubrication of the die, allowing wax to push lubricant into the folds or creases, giving the appearance of flow lines. 4. Chill breakthrough: is usually associated with; a) Chill too large b) Distorted chill c) Chill too small (floating to one side) d) Pips missing from the chill e) Sinks on the chill in pip location area f) Chill movement due to force of wax, especially if located near the sprue. 5. Incomplete coverage of chill: is associated with; a) Too much lubricant on chill b) Trapped air around the chill (injection rate too fast) c) Insufficient injection pressure 6. Orange peel effect is associated with; a) Die too cold b) Wax too cold c) Insufficient injection pressure 7. Misrun is usually associated with; a) Cold wax b) Cold die c) Injection rate too low d) Wax flow restriction in the die, predominately with thin wall sections 8. Cavitation is usually associated with; a) Die temperature too high b) Wax temperature too high c) Insufficient injection pressure d) Sprue too small e) Sprue in wrong position a. Chill left out of die b. Chill required c. Injecting a thick section through a thin section. This long list only highlights the many variables that exist during wax injection technology and the object is to illustrate how important it is for the foundry to check each area thoroughly.

1.6 PROBLEM DEFINITION

In the present study, an attempt has been made to produce awax blend which could offer better surface finish, minimumshrinkage and moderate hardness. Experiments wereconducted with different types of waxes namely Paraffinwax, Bees wax, Montan wax and Carnabua wax, varyingtheir proportions and stirring time. In each case propertiesof wax pattern like surface roughness and percentageshrinkage (linear/volumetric) were determined. Using thedata obtained from the experiments an attempt is made tofind out the set of input parameters, which could offer a setof ideal properties of the wax blend. Taguchi method wasused to optimize the process parameters.

Steps of the problem:

a) Selection of different wax blends for patternmaking.

b) Experimental determination of the wax blendsbehavior under different process parameters.

c) Experimental determination of shrinkage(linear/volumetric) and surface roughness of waxblend patterns produced.

d) Selection of best wax blend.

e) Optimization of process parameters by Taguchi method.

In the present study, thermal analyses like differential thermal analysis, thermo-mechanical analyses are used as aquality control check of wax blends. Shrinkage characteristics of waxes and their influences on the final dimensions of the wax patterns and castings are considered.The typical compositions and properties of the waxes usedin the present study are briefly described below.

A. **Bees wax:**This wax is a secretion of bees. Its main components arepalmitate, palmitoleate,hydroxylpalmitate and oleate estersof long chain alcohols (C30-32) (about 70 to 80% of thetotal weight). One of the properties of bees wax is that, itgives better surface finish.

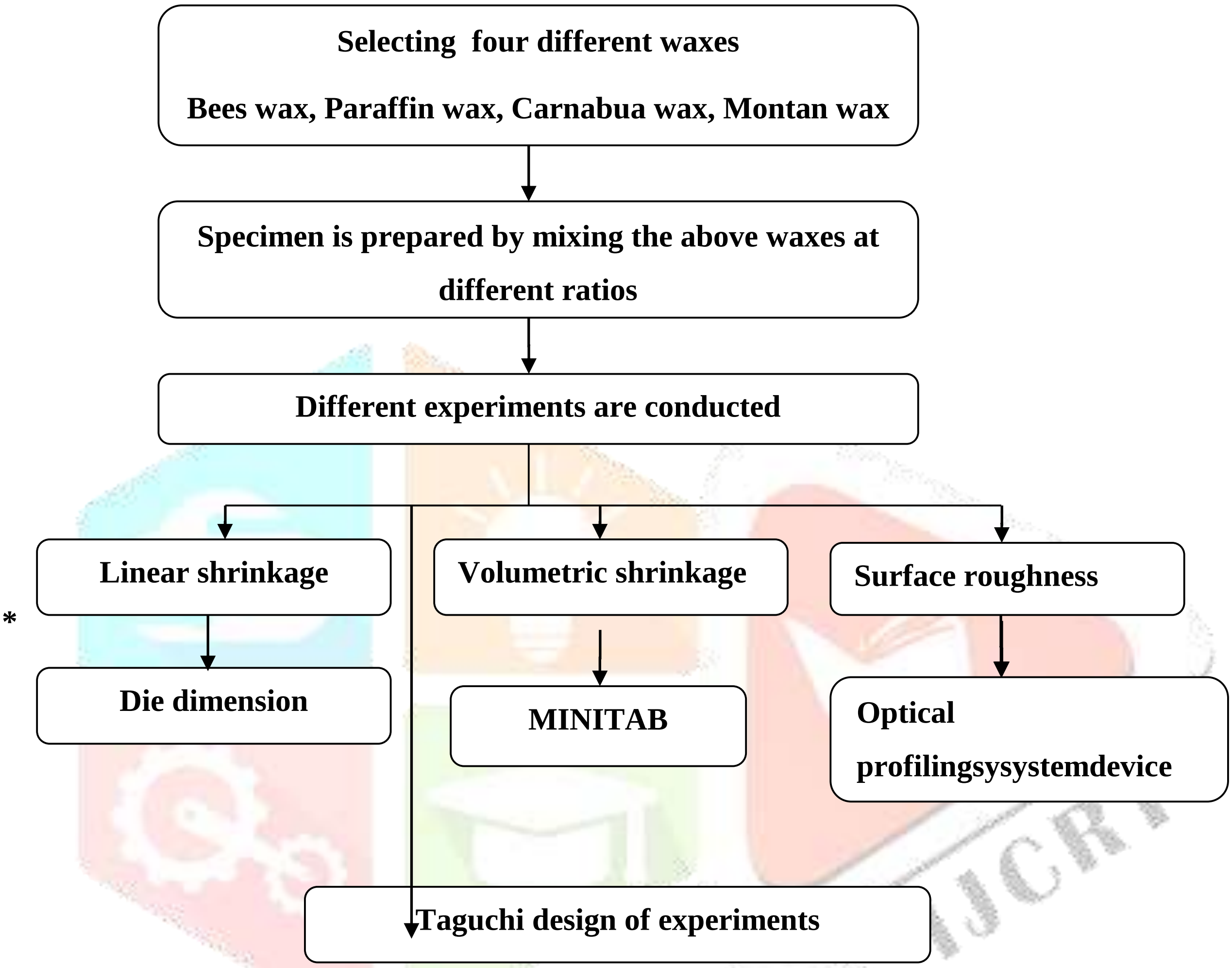
B. **Paraffin wax:**Paraffin is a class of aliphatic hydrocarbons characterizedby straight or branched carbon chains, generic formulaCnH2n+2.

Their physical properties vary with increasingmolecular weight from gases to waxy solids. Paraffin waxesare white, translucent, tasteless and odorless solidsconsisting of a mixture of solid hydrocarbons of highmolecular weight. They are soluble in benzene ligroin andwarm 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 byleaves of a Brazilian palm tree (*Coperniciapruniferacerifera*), about 100 g for one tree in a year. It containsmainly fatty esters (80-85%), free alcohols (10-15%), acids(3-6%) and hydrocarbons (1-3%). One of the properties ofcarnauba wax is that, it gives better dimensional accuracy.

D. **Montanwax**.This wax is derived by solvent extraction of lignite orbrown coal (sub-bituminous coal). The wax component ofMontan is a mixture of long chain (C24-C30) esters (62-68wt %), long-chain acids (22-26 wt %), and long chainalcohols, ketones, and hydrocarbons (7-15 wt %). Montanwax is hard and is most resistant to oxidation. Carbonpapers were the largest consumer of crude Montanwax.The highest present part (30%) of Montan wax is used incar polishes. Additional applications are shoe polishes,electrical insulators, and lubricant in plastics and in paperindustry.

1.7 METHODOLOGY



1.8 EXPERIMENTAL PROCEDURE AND MATERIALS

Four types of waxes namely paraffin wax, bees wax, montan wax and carnauba wax with different melting temperatures between 64 ^{0} C to 87 ^{0} C are selected for the present study. Each wax is in solid state at room temperature. The proportions selected in the formation of different wax blends are given in Table 2. The weight of each wax is measured with an electronic balance. The ingredients of each wax blend are mixed and melted at 120 ^{o}C in a metal container with constant agitation in order to get homogeneous melt.

Table 1.1: Properties of the waxes used

Sl no	Name of wax	Density (gm/cc)	Melting point (^{o} C)	Volumetric shrinkage (%)

1	Bees wax	0.97	65	7.25
2	Paraffin wax	0.78	64	6.20
3	Carnauba wax	0.99	87	4.20
4	Montan wax	1.02	82	2.45

Thermal analysis of waxes

The thermal analysis techniques used for measuring the effect of temperature on the blend sample are ThermoGravimetric Analysis (TGA), Differential ThermoGravimetric (DTG) and Differential Thermal Analysis (DTA). DTA is a technique which measures the difference in heat gained or lost by the sample, in comparison to a reference temperature during a temperature ramp. Temperature changes in the sample are due to endothermic or exothermic enthalpy transition or reaction such as those caused by phase changes, fusion, sublimation etc. DTG measures the loss in weight of a sample as it is heated. TGA is widely used to separate and quantify the components in a mixture. The thermal technique provides information concerning the thermal stability and composition of the sample and of any intermediate compound.

Pattern production

The four types of waxes are mixed together to produce different wax blends .The molten wax is then injected into the die. The die is heated up to 48 ^{o} C before injecting the wax and the wax injection temperature was raised up to 70 ^{o} C. After injecting the wax into the die, it is cooled down to the room temperature. Then the pattern is removed from the die. The parameters customarily controlled include wax temperature, injection temperature and injection pressure, die temperature, holding time.

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 additional 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. Wax patterns are generally injected at relatively low temperatures and pressures in split dies, using equipment specifically designed for this purpose.

Table 1.2 Range of process parameters

Process Parameters	**Range**
Injection temperature (A)	66 oC – 70 oC
Die temperature (B)	44 oC – 48 oC
Injection force (C)	440 N – 540 N

Holding time (D)	9 min – 11 min

a] Linear shrinkage

Linear shrinkage can be calculated by measuring thedifference between die dimensions and pattern dimensionsproduced.

b] Volumetric shrinkage

The Volumetric shrinkage is calculated as follows:

i. Apply a coating of grease on two halves of die tomake it leak-proof from water and align the twohalvesof die together.

ii. Fill the die cavity with water and measure itsvolume with the help of a measuring flask. (VD)

iii. Fill water in a measuring flask and note the initialreading. (Vi)

iv. Place the wax patterns made inside the measuringflask, volume rises and take the final reading. (Vf)

v. The difference between the two readings (Vf - Vi)gives the volume of pattern.

vi. The percentage of volumetric contraction of thepattern is given by{ ( )}*D f i* x 100*DV*

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

$\Delta V = \beta\ Vi\ (Ti - Tf)$

Where, ΔV = change in volume,β = volumetric coefficient of thermal expansion,Vi = initial volume,Ti = initial temperature.,Tf = final temperature

c] Surface roughness

Surface roughness is essential to measure the surface roughness of test wax patterns to establish the surface quality of the wax blends. Surface roughness of all the patterns was calculated in microns (μm) by using mitutoyo surface roughness tester. As the surface qualities of wax patterns are transferred to the ceramic shell and then to final casting therefore it is essential to check the surface finish of wax patterns. After solidification at room temperature, the blends were stored in air tight container to prevent them from moisture and dust.

Standard deviation, variance and probable error

Standard deviation of an infinite number of data is defined as the square root of the sum of the individual deviations squared, divided by the number of readings. Thus standard deviation s, variance v and probable error p, can be represented in equation

respectively.

$$s = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}}$$

Variance, v = $(s)^2$

Probable error, p = 0.6745s …

Hence standard deviation, variance and probable error of each dimension of patterns of all the five compositions can be calculated and mean standard deviation, mean variance and mean probable error of each blend can also be calculated.

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PERFORMANCE

Vertical Measurement Range 0.1 nm to 1 mm

Vertical Resolution1 < 1Å Ra

RMS Repeatability2 0.01 nm

Vertical Scan Speed up to 7.2 µm/sec (288 µin./sec)

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After injecting the wax into the die, it is cooled down to the room temperature. Then the pattern is removed from the die. The parameters customarily controlled include wax temperature, injection temperature and injection pressure, die temperature, holding time. The selected range of the process parameters is shown in the Table

Table 1.3 Range and levels of input process parameters

Factors	**Levels**		
	L1	**L2**	**L3**
Injection temperature (A)	66	68	70
Die temperature (B)	44	46	48
Injection force (C)	45	50	55
Holding time (D)	9	10	11

Sample Making

Table 1.4 Wax Samples

Sample no.	Paraffin wax	Bees wax	Montan wax	Carnauba wax
1	40	20	0	10
2	40	20	10	0
3	40	20	5	5
4	40	20	15	5
5	60	5	5	5
6	70	5	0	5
7	90	0	5	0
8	40	10	5	5
9	30	10	10	5
10	10	10	10	5

Table 1.5 Linear Shrinkage

Sample no.	Paraffin wax	Bees wax	Montan wax	Carnauba wax	Linear shrinkage %
1	40	20	0	10	1.5
2	40	20	10	0	1.3
3	40	20	5	5	1.23
4	40	20	15	5	1
5	60	5	5	5	1.2
6	70	5	0	5	1.3
7	90	0	5	0	1
8	40	10	5	5	1.4
9	30	10	10	5	2.78
10	10	10	10	5	2.9

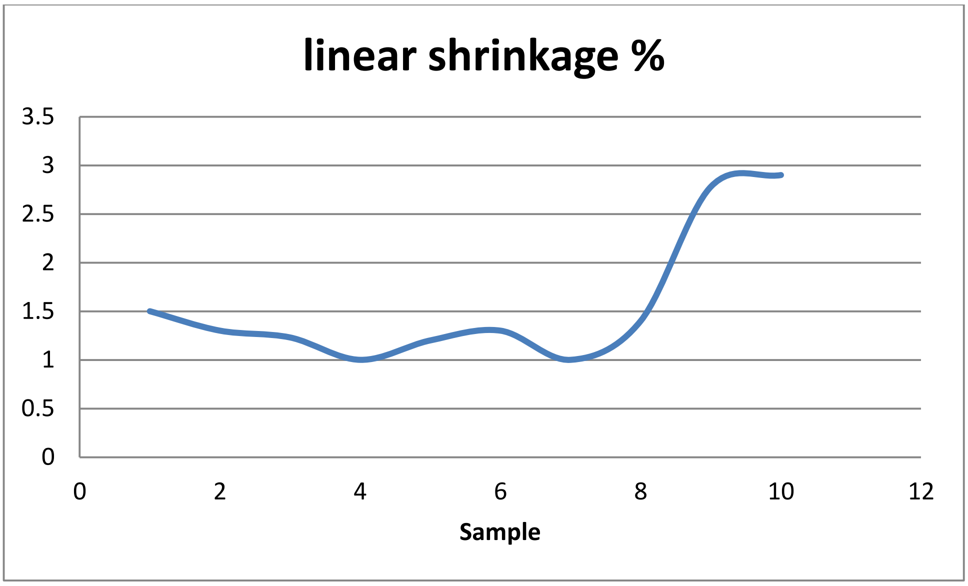

Table 1.6 Volumetric shrinkage

Sample no.	Paraffin wax	Bees wax	Montan wax	Carnauba wax	Volumetric shrinkage %
1	40	20	0	10	3.54
2	40	20	10	0	4.56
3	40	20	5	5	2.45
4	40	20	15	5	2.56
5	60	5	5	5	2.67
6	70	5	0	5	2.98
7	90	0	5	0	3.12
8	40	10	5	5	3.56
9	30	10	10	5	4.5
10	10	10	10	5	5.78

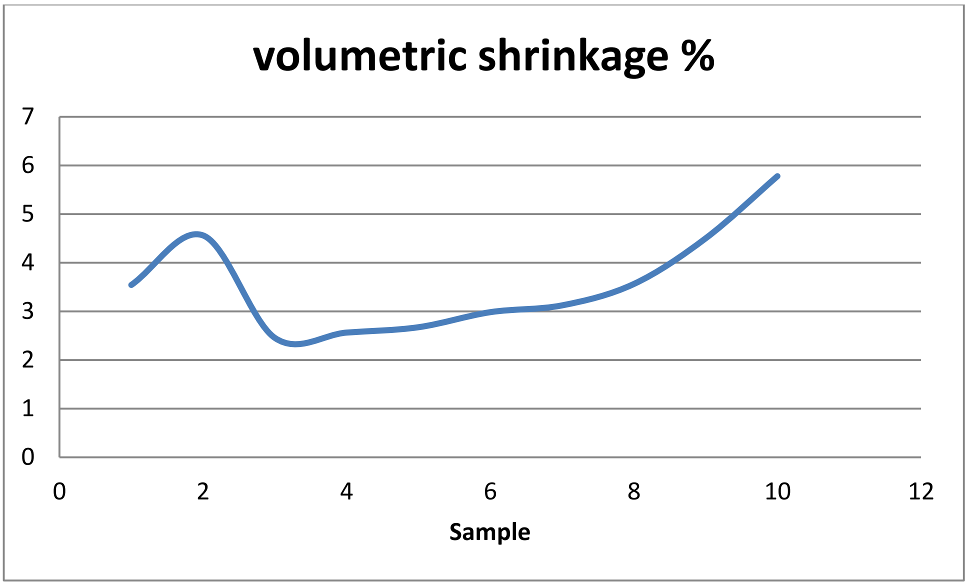

Table 1.7 Surface roughness

Sample no.	Paraffin wax	Bees wax	Montan wax	Carnauba wax	Surface roughness micrometer
1	40	20	0	10	2.63
2	40	20	10	0	2,11
3	40	20	5	5	1.97
4	40	20	15	5	1.54
5	60	5	5	5	2.02
6	70	5	0	5	2.45
7	90	0	5	0	2.62
8	40	10	5	5	2.56
9	30	10	10	5	2.67
10	10	10	10	5	2.78

1.9 TAGUCHI DESIGN OF EXPERIMENTS

From the experiments conducted, each wax blend underdifferent set of process parameters exhibited differentproperties. Yet, there exists a set of process parameterswhich could offer a set of ideal properties. Hence, anattempt is made to determine the optimum set of processparameters using Taguchi method. It is one of the mostimportant tool for studying the effect of various inputprocess parameters. For a particular defect in a wax patternproduction, the number of causes contributing to the defectmethods are too complex and difficult to use. Moreover, a large number of experiments are to be conducted that aretoo time consuming and expensive. Taguchi designed certain standard orthogonal arrays usingwhich simultaneous and independent evaluation of two or more parameters for their ability to affect the variability ofparticular process characteristics could be done in a minimum number of tests. The range and levels of selectedfactors (input process parameters)

1.10 OPTIMIZATION OF PROCESS PARAMETERS USING TAGUCHI METHOD

After conducting the experiments it will be observed that wax blends will be giving minimum shrinkage and better surface roughness. Taguchi optimization technique will be applied to wax blend , using Minitab software. The results of the investigationwill be shown

The heat capacity of the wax will be determined using differential scanning calorimeter tests on the different waxes. the results obtained for the two wax will be studied in the project. The shrinkage has not yet been totally characterized for the two waxes studied. According to what is done for plastic injection, the model that will be used should probably take into account a volumetric shrinkage, corresponding to the volumetric contraction due to the cooling of the part, a ‘‘crystallinity’’ shrinkage due to the change of phase from amorphous to crystalline, and a ‘‘mould restraint’’ shrinkage due to the relaxation of the residual stresses created by the mould during cooling

Filling simulations

Simulations will be carried out to determine the capability of the proposed models to predict the filling of themould. At the same time, some experimental work will be carried out using a transparent mould in order to be able tovisualize the wax flow. some comparison of the predicted and experimental flow front during the filling of the mould.

De-waxing

For the de-waxing process, the physical phenomena to be considered are: steam flow; steam condensation; wax fusion; wax flow; heat transfer in the shell; heat transfer in the wax;water penetration in the shell; heat exchange between the steam, the water and the shell; heat exchange between the shell, the water, the steam and the wax; and steam condensation. In the de-waxing process, the first problem is to determine what should be the limit of the proposed model. In the case of the wax injection, it is clear that if only the filling is considered,modelling the part should be enough. If the solidification and shrinkage are considered, then the mould should also be modelled. In the case of the de-waxing, if the aim is to determine the stress levels in the shell, then the steam perhaps can be ignored.

Then, the action of the steam can be taken into account through the boundary conditions. The steam flow, if it has to be modelled, can be described using a Newtonian model. Thus the viscosity of the steam can be described as function of pressure and temperature. For the change of phases, the pressure and temperature together with the phase diagram should be enough to determine the physical states of both wax and steam. The penetration of the water in the shell, which will no doubt affect the thermal conductivity of the shell, has to be described. As the scale of this problem is lower than the scale of the main problem, the stress in the shell, a function used as a boundary condition may be satisfactory to describe the water penetration phenomenon.

This function will be determined by studying the small scale pores phenomena, based on previous work on heat and mass transfer coupled with the evaporation/condensation phenomenon .This is at the present time just a proposal of models that can be used. The only theoretical study carried out on the de-waxing process known to the authors should be taken as a starting point.

OPTIMIZATION OF PROCESS PARAMETERS USING TAGUCHI METHOD

The minimum shrinkage was obtained by blend 4 so the optimization is applied on blend 4. The orthogonal array is given in Table 1.8

Table 1.8 Process Parameters Using Taguchi Method

Ex.No	Injection Temp ©	Die Temp ©	Injection force (N)	Holding Time	**Linear Shrinkage**	**Volumetric shrinkage**	**Surface roughness micrometer**
1	1	1	1	1	1	2.2	2.63
2	1	2	2	2	1.2	2.3	2,11
3	1	3	3	3	1.5	2.4	1.97
4	**2**	**1**	**2**	**3**	**1.3**	**2.5**	**1.54**
5	2	2	3	1	1.4	2.22	2.02
6	2	3	1	2	1.32	2.33	2.45
7	3	1	3	2	1.42	2.55	2.62
8	3	2	1	3	1.44	2.65	2.56
9	3	3	2	1	1.33	2.77	2.67
							2.78

1.11 CONCLUSION

The following conclusions are drawn out of the experiments conducted on wax blend selection and selection of optimum process parameters by Taguchi method.

1. The wax blend 4 with proportion of 40% paraffin
wax, 20% bees wax, 15% montan wax and 5% carnauba wax gives the better results of linear shrinkage, volumetric shrinkage and surface roughness.
2. The optimized process parameters (using Taguchi method) are: 68 ^{o}C (injection temperature), 46 ^{o}C (die temperature), 490 N (injection force) and 10 minutes (holding time).

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