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"Mitigation of Shrinkage Defects in Investment Casting Process through Taguchi Method"

Vinish Garg[1], Dr. Mohammad Israr[2], Dr. Anshul Gangele[3]

[1]*Assistant Professor, ITM Universe, Gwalior, M.P.*

[2]*Principal, Dungarpur College of Engineering & Technology, Dungarpur, Rajasthan, India*

[3]*Professor and Head, Department of Mechanical Engineering, Medi-Caps University, Indore, MP, India*

Abstract: **The aim of the paper is reduction & mitigation of shrinkage defects in the investment casting process. For this purpose design of experiment approach is used using Taguchi's Offline (Orthogonal Array) method optimizing process parameters leading to improved properties of casting. The investment casting process considered for study involves plaster of Paris as a mould material as it results in improved the properties like tensile strength, hardness and surface finish of A443 alloy by adding the trace element because A443 alloy has maximum shrinkage in all aluminum alloys.**

Keywords: **Investment Casting, Shrinkage Defects, Designs of Experiments, Taguchi's Method, Optimization**

I. INTRODUCTION & LITERATURE REVIEW

Investment casting is a widely used technique for modern metal casting, and provides an economical means of mass producing shaped metal parts containing complex features. The investment casting process involves the production of engineering castings using an expandable pattern. Investment casting is also known for producing the intricate details and high dimensional accuracy.

The investment casting process has increasingly been used to produce components for the aerospace industry and it has been particularly successful for the production of single crystal turbine blades.

Sabau explains the effect of addition of the additives to the wax. Additives used for making investment casting waxes include a variety of materials such as resins, plastics, fillers, oils and plasticizers. Resins are added to the blend to increase strength.**Gebelin** concluded accuracy of the wax patterns used in the investment casting process has a direct bearing on the accuracy achievable in the final cast part. **Liu** proposed on new investment casting technology, 'freeze cast process' with ice as pattern. **Rezavand** made an experimental study on dimensional stability of simplified wax models. The dimensional accuracy of wax injection step introduces a great influence on the final dimension and thus on finishing process. The focus of this experimental work was on the injection stage, investigating the effects of processing parameters and the shrinkage of critical dimensions.

Yarlagadda and Hock determined the accuracy of wax patterns produced by hard (polyurethane mould) and soft (RTV mold) tooling and optimized the injection parameters used in a low-pressure injection molding.**Horacek and Lubos** studied the influence of injection parameters on the dimensional stability of wax patterns produced by injection molding process. They found an interrelationship between various injection parameters and their dependency on some dimensional parameters.

Liu concluded that proper choice of stucco flours during primary and backup coating is an important aspect of shelling to provide shells consistent porosity, thickness d strength. Zircon sand with an AFS grain fineness range of 100-110 is advisable to use as primary stucco whereas fsed silica or alumino silicate for backup coats similar as the refractory powders. The intermediate stucco usually a -30 +80 mesh is recommended which allows a denser, stronger shell to be built.**Jones and Marquis** concluded that the coating materials for ceramic shell investment casting molds fall in three major categories: binders and catalyst, refractory fillers and additives. **Beeley and Smart** found that selection of any refractory filler material for shell making is dependent on a wide variety of factors which can affect the properties of investment slurry, shell and casting and also the economy of the process. **B Singh, P Kumar, B. K. Mishra** focussed on the study of the effect of primary slurry parameters on the ceramic retention test. They calculated the variations in coating thickness for slurry and ceramic shell moulds made on wax plate using primary slurry and coarse fused-silica sand as stucco. **McGuire** found that fused silica has an extremely low coefficient of thermal expansion and can therefore be used to produce a dimensionally stable ceramic mold. Fused silica is a non-reactive filler and is easier to remove after casting in the knockout and cleanup operations. Fused silica also has good thermal shock resistance and is dimensionally very stable.

Bijvoet 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.

Jones and Yuan found that a weakened ceramic shell structure can lower the quality of an investment casting. The strength of a ceramic shell mould is a function of such factors as: mould material, shell build-up procedure, and firing procedure. **Baumeister** explains the influence of casting parameters on the microstructure and the mechanical properties of extremely small parts produced by microcasting.They evaluated how the combinations of process parameters that result either in maximum yield strength or maximum ductility also affect the fatigue life of components. The influence of some casting and heat-treatment parameters affecting microstructure (e.g., dendritic arm spacing, silicon- eutectic structure, and precipitation of agehardening phases) is assessed on both the static tensile properties and fatigue life.

S. Lun Sin, D. Dube, and R. Tremblay proposed that influence of process parameters and wall thickness on the microstructure and tensile properties of cast specimens was studied. **Qingbin Liu, and C. Leu** described in this paper is aimed at investigating the dimensional accuracy and surface finish of metal parts made by investment casting with ice patterns generated by rapid freeze prototyping. **Adrian s. Sabau** carried out the experimental measurements and numerical predictions of alloy shrinkage factors (SFs) related to the investment casting process. The dimensions of the A356 aluminum alloy casting were determined from the numerical simulation results of solidification, heat transfer, fluid dynamics, and deformation phenomena.

This paper focuses on the fact that in investment casting process the shrinkage defects is the most commonly defects which causes dimensional changes, is the result of the following three sequential events:
(1) Contraction of the molten metal as it cools prior to solidification. (2) Contraction of the metal during the phase change from liquid to solid. (3) Contraction of the solidified metal (the casting) as its temperature drops to ambient temperature.

II. Selection Of Process Parameters

Taguchi Method

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

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

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

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

Experimental design strategy

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

In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives:

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

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

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

(DOF)R = degree's of freedom
P = number of factors
L = number of levels

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

However, total DOF of the orthogonal array (OA) should be greater than or equal to the total DOF required for the experiment.

Thus, we selected the L9 orthogonal array to make the further experiments. This array specifies 9 experiments. The L9 OA with 4 factors, 3 levels and its responses are shown in the Table 3.1.

Table 3.1: L9 Orthogonal Array

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

The stages to go through are as follows

1. Selection of the factors to be evaluated.
2. Selection of number of levels.
3. Selection of appropriate orthogonal array.
4. Assignment of factors to the columns.
5. Conduct the experiment.
6. Analyze the results

Selection Of Coating Materials

Selection of shell mould material is of importance to the successful production of high quality cast parts. Shell materials need to be of sufficiently high refractoriness. As a general practice, high refractory face coat slurry is normally applied to the wax pattern to improve refractoriness. Shells must have sufficient high temperature mechanical stability to ensure dimensional accuracy of cast parts as well. Much of observed defects in a cast part are actually a result of faulty shell mold production. The shell materials used, compositions are given below.

Slurry material

The materials used for preparing the slurry are as follows:

a) Plaster of Paris: Plaster of Paris has been used as the slurry to be coated over the pattern which latter solidifies to form the mould material. Plaster of Paris is considered to be one of the best molding materials rendering castings with the required dimensional tolerance and average surface finish. The advantage of plaster of paris is that it mixes with water easily and produce hard smooth and chip resistant surface. Major drawback of the slurry material is that it has got low or negligible permeability and also is a bad conductor of heat.

b) Sand: Sand must be able to withstand high temperatures and pressure, allow gases to escape, have a uniform, small grain size and be non-reactive with metals. So silica sand is used with the plaster of paris to increase its permeability.

Selection Of Casting Material

In the present investigation A443 aluminum alloy has been taken to make the castings. A443 alloy comprises Silicon (4.5-6.0%), Copper (0.6%), Magnesium (0.5%), Zinc (0.5%), Manganese (0.5%) and aluminum as the balance. It is a high strength and low weight alloy used in aerospace engineering application. Owing to their good corrosion properties, high specific strength and low costs for shape forming, cast aluminum alloys are wised used in engineering applications, such as engines for vehicles, helicopters and fan hubs, etc. Due to its above features it could also be used in making engine blocks and other automotive parts. But having the above properties it has the maximum shrinkage porosity. So we select the A443 aluminum alloy because our aim is to reduce the shrinkage defects in the casting.

To reduce the shrinkage defects from the casting a trace element is added in the A443 aluminum alloy. Trace elements are those elements which belong to the I and II groups of periodic table, used in this investigation because trace elements provides the strength to the casting. The trace elements are Hydrogen(H), Lithium(Li), Sodiun(Na), Potassium(K), Rubidium(Rb), Caesium(Cs), francium(Fr), Beryllium(Be), Magnesium(Mg), Calsium(Ca), Sr, Barium(Ba), and Radium(Ra). In this present investigation we use the Potassium (K) which has a melting point of 63.38°C.

Elements %	Si	Cu	Mg	Mn	Zn	Ti	K	Al
A443 alloy without Trace element	6.00	0.60	0.05	0.50	0.50	0.25	-	balance
A443 alloy with trace element	6.00	0.60	0.05	0.50	0.50	0.25	0.50	balance

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Selection Of Casting Parameters

One of the key demands for better tolerances in the investment casting is to calculate and control the shrinkage of pattern material to improve the accuracy of products. Shrinkage characteristics of waxs and its influence on the final dimensions are of great fundamental importance in getting high quality castings, minimizing product cost and scrap. Based on the review of literature the process variables play an important role in the accuracy of the cast parts.

The following process variables were selected to visualize their effect on the dimensional accuracy and surface roughness of the cast parts:

a) Pouring temperature
b) Preheat temperature
c) Preheat time

The above process variables were selected to visualize their effect on dimensional accuracy, surface finish and mechanical properties of cast parts produced for investment casting process. From the literature review the ranges were selected for the study are shown in the table. Further these ranges that were divided into the three levels according to the Taguchi method are as shown in the table 1.2

Table 1.2.:
Process variables and their range with levels

Factors	Range	Levels		
		L1	L2	L3
Preheat temperature (A)	150oC – 300oC	150	225	300
Pouring temperature (B)	700oC –750oC	700	725	750
Preheat time (C)	2 – 6 hrs	2	4	6

Experimental Procedure

There are three major stages in ceramic shell investment casting process: the production of wax patterns, the production of the ceramic moulds and the production of metal casting. Pattern dies are used to create wax patterns by injecting wax into dies. The wax patterns are used to create a ceramic shell by the application of a series of ceramic coatings, and the alloy is cast into the dewaxed shell mold.

III. Mould Preparation And Casting

Mould with the desire shape need to be formed before casting. The procedures of the mould making and the casting is describes in the following sections.

Pattern die

Pattern dies may be made either by casting a low melting point alloy around a (metal) master pattern or by machining cavities in two or more matching blocks of steel . For long production steel dies are suitable because they are machined from the solid blocks by die sinking and are assembled in the tool room.

The dies thus formed, achieve the highest standard of accuracy and have considerable longer life. Dies of low melting point alloys are made by casting and require a master pattern or metal replica of the final casting. The master pattern is given an allowance for subsequent contractions of pattern and metal, up to 2%. The master pattern is used to produce two halves of the die or mould by embedding it in plaster or clay and casting one die half at a time by pouring a low melting point alloy such as that of bismuth or lead. Die halves are sent for necessary machining and drilling the gate through which wax is to be injected for preparing expendable patterns. Cast dies are more economical than sunk dies for short production runs. Die dimensions are re-worked by trial-and-error procedures until casting dimensions are reduced within acceptable dimensional tolerances, increasing the cost of the castings. For sake of simplicity, it was decided to select a die capable of producing only a single pattern weighing approximately 180 gm. The master pattern used in the present study is shown in Figure 1.1. It was used to produce two halves of the die. The master pattern is given an allowance for subsequent contractions of pattern and metal. Brass is used as a die material.

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Figure 1.1: Pattern die

Production of the patterns

The wax patterns used for preparation of investment casting moulds consist of a mixture of 55% paraffin wax and 25% bees wax and 20% montan wax. First of all, the die was placed on a brick.

The wax is then heated up to 80°C which is slightly above the melting point of the wax by using an electrical resistance heater inside a small container. The molten wax is then poured into the die. After that, the patterns are left to cool in room temperature for an approximately 1 hour. This is to ensure that the wax is completely solidified. After that, the pattern is removed.

Figure 1.2 Wax Patterns

IV. Mixture Of The Slurry

Shell materials need to be of sufficiently high refractoriness. As a general practice, high refractory face coat slurry is normally applied to the wax pattern to improve refractoriness. Shells must have sufficient high temperature mechanical stability to ensure dimensional accuracy of cast parts as well. Much of observed defects in a cast part are actually a result of faulty shell mold production.

Plaster of Paris has been used as the slurry to be coated over the pattern which latter solidifies to form the mould material. Plaster of Paris is considered to be one of the best moulding materials rendering castings with the required dimensional tolerance and average surface finish.

Major drawback of the slurry material is that it has got low or negligible permeability and also is a bad conductor of heat. Sand is used with the plaster of paris to increase its permeability. In the present work 40 percent of sand by weight has been mixed to the 60 percent plaster of Paris by weight so as to increase its permeability. For preparation of slurry, the ingredients are accurately weighed. The mixture is then stirred for few minutes, covered and left for aging for approximately 18 hours. At the end of aging period, measured quantity of filler is added slowly to slurry followed by stirring. Mixture is then stirred by an impeller run by motor in a mixer for approximately 72 hours as shown in figure 1.3.

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Figure 1.3: The mixture of slurry

4.1.4 Shell mould making

When the slurry is ready, the pattern is dipped into the slurry. The pattern is then left to dry in the room temperature for about two hours. This is to ensure that the mould is completely dry before the next dipping process. The dipping process is repeated until the desired layers of the mould are achieved. The desired layers are 5, 7, 9 and 11 layers. Figure 4.3 shows the mould with 7 layers. When the last coat is applied, the moulds are then let to dry in room temperature for about 16 to 48 hours. This is to ensure that the mould is completely dry to reduce or avoid cracking of the mould during de-waxing.

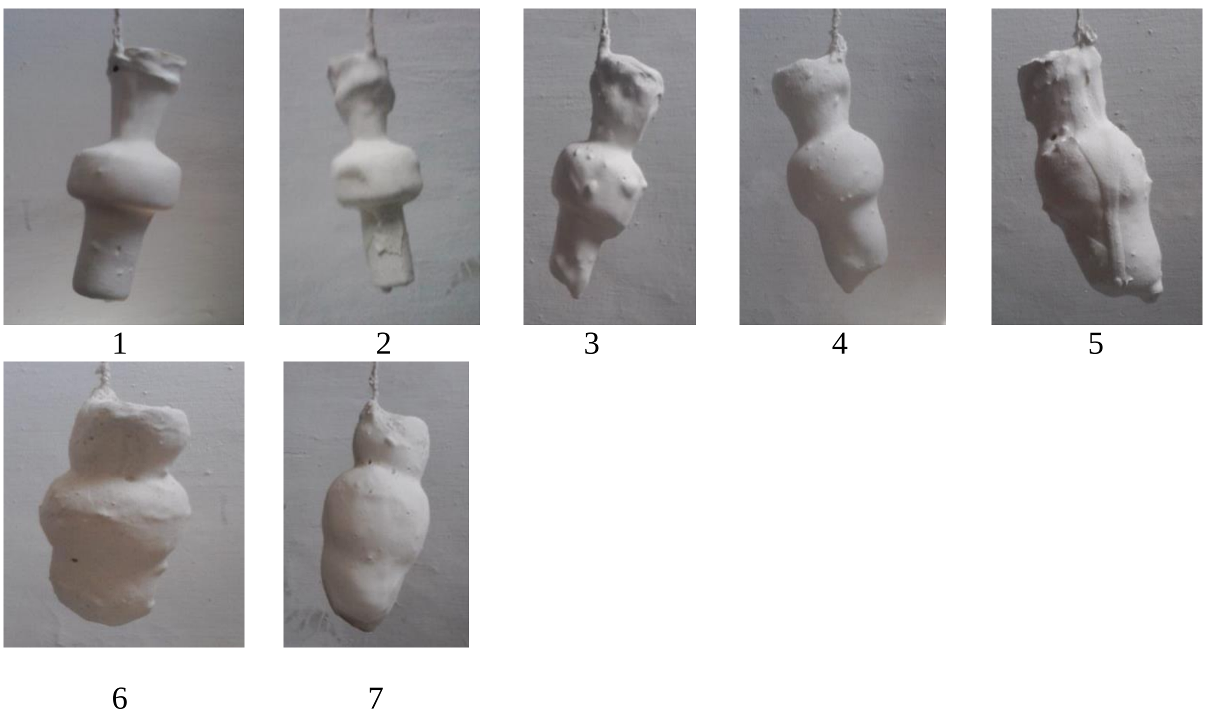

Figure 1.4: Mould with 7 layers

4.1.5 De-waxing device

The primary objective of de-waxing system is to remove the wax from the shell without cracking it. The second main objective is to drain out the melted wax out of the oven without burning or decomposing.

Successful de-waxing depends on sound design of equipment for applying sufficient heat to the exterior of the ceramic shell so that a thin skin of wax adjacent to the primary coat melts before the bulk of the wax can expand and exert enough pressure to crack the shell. The de-waxing device is as shown in figure

4.1.6 Firing of mould

Solid moulds are placed upside down in furnaces. First of all, the wax pattern is melted and the wax is drained from the mould. The oven which melts wax is kept at a temperature of 150**oC** to 300**oC.** After removing the wax, the shell can be quickly fired at a desired temperature.

Firing of mould brings full development of dry strength, eliminates traces of organic material and preheats the mould to casting temperature, thus facilitating metal flow and reproduction of mould details. After de-waxing and firing of shell mold the molten metal is poured in the shell to make the casting, but to check the good surface finish and better shape of casting.

Melting and pouring of metal

The metal to be pour is melted in an induction furnace and brought in a small ladle to preheated moulds for pouring. The figure 1.6 shows pouring the molten metal and shell after pouring of molten metal. Moulds are preheated (before getting poured) to about 1100 0C depending upon the metal to be poured e.g., for light alloys and for steels, the preheated mould temperatures should be of the order of 300 0C to 500 0C and 800 0C to 1100 0C respectively. For preparing casting of non-ferrous alloy, Al-Si alloy was selected because of its good castability characteristics. Silicon is good in metallic alloys used for casting. This is because it increases the fluidity of the melt, reduces the melting temperature, decreases the contraction associated with solidification and is very cheap as a raw material.

(a) (b) (c)

Figure 1.6: (a) Melting of alloy, (b) Metal pouring, (c) Mold shell after metal pouring

Figure 1.7: Photograph of Casting

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After pouring of metal the shell is hammered to release the casting. The figure 4.7 shows the casting of A443 alloy without trace element and A443 alloy with trace elements. After a visual inspection it is clearly see that the casting with tag number 1.1 which is cast by A443 alloy has shrinkage porosity and the casting with tag number 2.1 cast by A443 alloy with trace element has better casting. It means that after adding a trace element in aluminum alloy the casting is better. Now after casting next step is the measurement of the properties of both type of casting.

Measurement Of Casting Properties

After the casting the following properties are measured.

1) Volumetric shrinkage
2) Surface roughness
3) Hardness
4) Tensile strength

The measurement of these properties is explained as follows:

1) Volumetric shrinkage

The Volumetric shrinkage is calculated as follows

a) Fill water in a measuring flask and note the initial reading. (Vi)
b) Place the casting without shrinkage inside the measuring flask, volume rises and take the final reading. (Vf)
c) The difference between the two readings gives the amount of volume of casting without shrinkage.
d) The above process is repeated for casting with shrinkage.
e) The percentage of volumetric shrinkage given by % VS= [(Volume of casting without shrinkage - Volume of casting with shrinkage)/Volume of casting without shrinkage] *100

2) Surface roughness

Surface roughness of the each sample is measured by using Optical Profiling System device which is of the type Veeco WYKO NTI 100. Three readings of average surface roughness (Ra) on top, bottom and left side surface is taken for specimen. Mean of these three observations is taken as representative value of respective surface roughness.

Fig 1.8: Optical profile meter

3) Hardness

Hardness is a characteristic of a solid material expressing its resistance to permanent or plastic deformation.

4) Tensile strength

The tensile test of A443 aluminium alloy with and without trace element is performed on UTM (Universal Testing Machine).

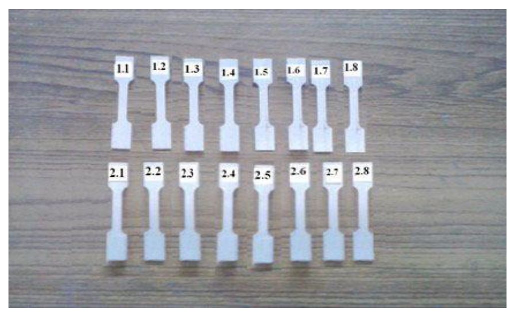

Figure 1.10: Specimen for tensile tests

V. RESULTS AND DISCUSSION

Here a number of experiments are carried with the varying process parameters with their different levels and optimizing these process parameters. The average hardness of casting, tensile strength of casting, and surface roughness of casting are calculated from the measured data. The average properties of the experiments are as shown in table 1.1.

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Casting	Average Tensile strength(MPa)	Average Surface roughness (µm)	Average BHN	Average Volume (cc)
1	3.07	43.24	136.68	37.44
2	2.61	44.86	140.96	38.22

Casting 1 indicates the casting by A443 aluminium alloy without trace element
Casting 2 indicates the casting by A443 aluminium alloy with trace element

The results obtained by the experiments on both type of casting are tabulated in the table 1.2 and 1.3

Table 1.2:
Experimental data of A443 aluminium alloy casting without trace element

Expt. No.	Process variables			Measured properties			
	Pouring temperature (°C)	Preheat temperature (°C)	Preheat time (hrs)	Surface roughness (µm)	Hardness (BHN)	Tensile strength (MPa)	Volume (cc)
1	700	150	2	3.96	42.1	135.05	38
2	700	225	4	2.88	39.67	128.63	36
3	700	300	6	3.02	44.23	138.2	37
4	725	150	4	2.675	43.17	139.36	36
5	725	225	6	2.96	45.5	134.98	36
6	725	300	2	3.02	46.23	137.87	40
7	750	150	6	2.57	41.51	138.75	37
8	750	225	2	3.63	43.52	140.6	39
9	750	300	4	2.962	43.26	136.63	38
			Avg	3.07	43.24	136.68	37.44

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Table 1.3:
Experimental data of A443 aluminium alloy casting with trace element

Expt. No.	Process variables			Measured properties			
	Pouring temperature (°C)	Preheat temperature (°C)	Preheat time (hrs)	Surface roughness (µm)	Hardness (BHN)	Tensile strength (MPa)	Volume (cc)
1	700	150	2	3.02	41.1	137.33	39
2	700	225	4	2.12	42.26	145.68	36
3	700	300	6	1.97	44.53	141.98	38
4	725	150	4	3.26	45.53	139.22	37
5	725	225	6	2.36	47.55	138.15	38
6	725	300	2	3.02	44.4	142.12	41
7	750	150	6	2.52	45.26	140.69	38
8	750	225	2	2.01	47.87	144.33	40
9	750	300	4	3.25	46.63	139.21	39
			Avg	2.61	44.86	140.96	38.22

VI. CONCLUSION

The following conclusions have been drawn from the present investigation.

1. Plaster of paris is one of the most shell mould material because of the excellent surface finish and it easily mixed with water.
2. It is possible to reduce the shrinkage defects by adding the trace element in aluminum alloy and improve the properties effectively by controlling the process parameters.
3. For reducing the volumetric shrinkage the selected values of process parameters are:

i. Pouring temperature 750ºC
ii. Preheat temperature 300ºC
iii. Preheat time 2 hrs

4. Pouring temperature, preheat temperature and preheat time affects significantly the surface finish of A443 alloy with trace element casting compare to the A443 alloy without trace element casting in the investment casting process. For the hardness, hardness should be maximum. Selected values for parameters:

iv. Pouring temperature 750ºC
v. Preheat temperature 225ºC
vi. Preheat time 4 hrs

5. For surface finish we conclude that surface roughness is minimized by keeping the pouring temperature, preheat temperature and reheat time at low level. Selected values of process parameters are:

i. Pouring temperature 700ºC
ii. Preheat temperature 225ºC
iii. Preheat time 2 hrs

6. For tensile strength, the strength should be maximum. So selected values for process parameters are:

i. Pouring temperature 700ºC
ii. Preheat temperature 225ºC
iii. Preheat time 4 hrs

7. The optimum process parameters which gives minimum shrinkage, surface roughness, maximum hardness and tensile strength are as follows: 0.85%, 2.16 µm, 46.58 BHN and 142.72MPa respectively.

The future work can be extended by effect of process variables on the standardized shell mould properties.I t may involve varying the process variables on shell mould, measure the shell properties & process variables optimization.

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