PRODUCTION OF A SAMPLE AUTOMOTIVE PART BY INTEGRATION OF RAPID PROTOTYPING AND A PRECISION CASTING PROCESS

by

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ABSTRACT

PRODUCTION OF A SAMPLE AUTOMOTIVE PART BY INTEGRATION OF RAPID PROTOTYPING AND A PRECISION CASTING PROCESS

The goal in the manufacturing arena is to present new products from concept to market quickly and inexpensively. Introducing new products at ever increasing rates is very critical for remaining succesful in a competitive global economy. To integrate all prototyping, manufacturing and optimizing studies in order to decrease the product development cycle time is one of the major concerns of all engineering fields.

In the present study, plaster mold casting process is chosen as the precision casting method for prototyping and manufacturing of a sample automative part. This process is first examined using Taguchi and mixture design of experiments to optimize some of its process parameters.

Experimental results show that the cycle time can be decreased by increasing temperature and mixing time. Some industrial waste products such as fly ash and polymer additives can be used for stabilizing the molding process and increasing the surface quality of the castings.

ÖZET

ÖRNEK BİR OTOMOBİL PARÇASININ HIZLI PROTOTİPLEME VE HASSAS DÖKÜM YÖNTEMLERİNİN BİRLEŞTİRİLMESİ İLE ÜRETİMİ

Üretim endüstrisin temel amacı, değişen pazar koşullarına uygun hızlı ve düşük maliyetli yeni ürünleri ortaya çıkarmaktır. Mevcut dünya ekonomisi, üretim şirketlerini gün geçtikçe daha hızlı ürün geliştirme konusunda zorlamaktadır. Tüm prototip, üretim ve yeniden değerlendirme süreçlerinin birleşik ve eşzamanlı hale getirilerek, yeni ürünün pazara sunum süresinin kısaltılması, bütün mühendislik disiplinlerinin ortak çalışma alanıdır.

Bu tez çalışmasında bir hassas döküm yöntemi olarak, alçı kalıba döküm seçilmiştir. Deneysel çalışmalar öncesi, dökülen parçanın fiziksel özellikleri ile imalat parametrelerini incelemek amacıyla Taguchi ve istatiksel karışım analiz yöntemleri uygulanmıştır.

Yapılan deneysel çalışma sonucunda; döküm işleminin ve dolayısıyla tüm imalat sürecinin, sıcaklık ve karışım zamanlarının arttırılmasıyla kısaltılabileceği görülmüştür. Endüstriyel atıklardan, uçucu kül ve kil (polimer) katkılarının karışıma eklenmesiyle, kalıp ve döküm yüzey kalitelerinin olumlu yönde etkilendiği ve proses değişkenliğinin azaldığı görülmüştür.

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LIST OF SYMBOLS/ABBREVIATIONS

A	Estimate of main effect A
B	Estimate of main effect A
C	Estimate of main effect A
I	The identity element
k	The loss constant
L	The loss at the specification limit
m	The mean target value
X	The matrix of the levels of the variables
y	The value of the response
α	Row effect
β	Column effect
β_{LE}	Vector of least square estimators
ε	Random error
σ	Variance of the data
σ_y	Variance of the sample mean
τ	Treatment effect
AFS	American Foundries Society
LE	Least square function
MS	Mean square
SS	Sum of squares

1. INTRODUCTION

The word manufacture is derived from two Latin words manus (hand) and factus (make); the combination means made by hand. Technologically, manufacturing is the application of physical and chemical processes to alter the geometry, properties and/or appearance of a given starting material to make parts or products; manufacturing also includes the assembly of multiple parts to make products [1].

The history of manufacturing can be separated into two subjects [1]:

- The discovery and invention of materials and processes to make things.
- The development of systems of manufacturing.

Systems of manufacturing refer to ways of organizing people and equipment so that the production can be performed more efficiently [1].

Casting is a manufacturing process which molten metal flows by gravity or other force into a mold where it solidifies in the shape of the mold cavity. Casting of metals can be traced back to around 4000 B.C. It was the subsequent discovery of copper that gave rise to the need for casting [1].

Historians believe that hundreds of years elapsed before the process of casting copper was first performed, probably by accident during the reduction of copper ore in preparation for hammering the metal into some useful form. It is likely that the discovery occurred in Mesopotamia, and the technology quickly spread throughout the rest of the ancient world.

Casting processes are divided into two broad categories according to type of mold used:

- Expandable mold casting processes.
- Permanent mold casting processes [1].

An expandable mold in casting means that the mold in which the molten metal solidifies must be destroyed in order to remove the casting. Molds are made of sand, plaster and similar materials. A permanent mold is one that can be used over and over to produce many castings. It is made of metal or ceramic refractory material that can withstand the high temperatures of the casting operation [1].

In plaster mold casting, a permanent pattern is surrounded by a gypsum-based slurry, which sets to a solid, self-supporting mold, rigid enough to be handled. The mold parts are then stripped from the pattern and baked or burned out to remove moisture. The viscosity of the plaster allows it to flow around the pattern to form a mold with excellent detail and finish with minimum of skilled labor. The mold material does not have to be heated, rammed, vibrated or pressed while it is poured [2].

The Taguchi method of experimental design is very well suited to improving casting processes for several reasons. First it is very efficient and easy to apply, so that it does not require large amounts of time or resources to conduct a given set of experiments. Second, the effect of many different process variables can be examined simultaneously, which ensures that beneficial factor combinations are not overlooked. Finally, using a Taguchi signal to noise ratio leads to concurrent optimization of the process and reduction of process variability [3].

Before the experimental work of this thesis, the Taguchi and mixture design approaches were utilized to optimize the various parameters of the plaster mold casting of a automotive part namely, front engine cover of a diesel engine.

2. LITERATURE SURVEY

2.1. Plaster Mold Casting

2.1.1. Definition

The plaster mold casting process is a specialized process used for the production of non-ferrous alloy castings with smoother surfaces more finely. This process is basically similar to that of sand casting in that the mold usually made in two halves corresponding to the cope and drag of sand molding is assembled for pouring of the metal. The true plaster mold casting process is based on the use of a permanent pattern.

In the commercial production of castings, four variants of the process are used [4].

- The conventional plaster mold casting process.
- The foamed plaster process.
- The Antioch process.
- Match plate pattern process.

2.1.2. Applications

Plaster mold castings are applied best where the need for thin walls accuracy and good surface finish justifies their cost. These castings may range in size from fractions of a gram to hundreds of kilograms, with the upper limit determined by the oven capacity. Small castings up to 10 cm^2 size can often be produced by the investment, since many patterns can be invested in one mold. In larger sizes; plaster molds tend to be cheaper to produce than investment molds, and accuracy is generally better, since the intermediate stage involving a relatively flimsy expandable pattern is eliminated. Prototype and preproduction castings can be made in plaster molds, even when the designer intends to use die casting in production, because of the lower cost and faster delivery of plaster mold tooling. Generally the male tooling used in plaster casting is easier and cheaper to change than are the dies used in die casting [5].

Molds for the plastic and rubber industry are frequently produced by casting plaster molds. The ability to use flexible pattern material is especially valuable because many of these molds are undercut. Tire molds, for example are commonly aluminum castings from plaster molds made with flexible rubber patterns. A good plaster mold can often be produced in much less time is needed to machine a mold out of a solid, and it can be used with no further work. The relatively low rate of production in plaster mold casting is often offset by the small casting quantities usually required. There is also a growing use of plaster cores in sand or semi permanent molds, either to improve accuracy and finish or to improve thermal gradients and cooling rates in the molds. However, plaster mold castings are competitive with sand castings only when a considerable amount of machining can be eliminated by the use of plaster molds [5].

2.1.3. Finishes and Tolerances

Characteristic features of the process include excellent surface finish and detail, similar to that of high quality die-castings. As cast finish can be 1,2 to 4 µm rms. The insulating properties of plaster molds allow thinner walls to be cast than are possible by any other casting process. The thickness possible depends on the area to be cast, but 0.5 mm thickness have been cast in some instances [6].

Complex configurations, especially, lend themselves to the plaster mold process. While it is not possible to meet machining tolerances, as cast tolerances achieved by plaster-mold castings are often satisfactory with suitable designs. Small holes cannot be easily cast with plaster molds unless they are very shallow, because of the low mechanical properties of the mold materials. It is cheaper to drill small holes where possible. In the conventional process, plaster of paris is mixed with water to produce a slurry which is poured over a permanent pattern contained within a molding box. Upon setting a rigid mold is produced which, after pattern stripping, is dried at an elevated temperature to remove free and chemically combined water before the metal is cast into the mold. This method produces a strong, dense but inherently impermeable mold. Hence, metal casting must be conducted using vacuum and/or pressure assistance to ensure complete filling of the mold by the metal. The insulating nature of the plaster improves the fluid life of the mold by the metal, which aids mold filling and thin section production [6].

The foamed plaster variant produces permeable molds through the incorporation of air into the slurry at the mixing stage. It is possible to produce a mold in which 50 per cent of the volume consists of air bubbles. This has the desired effect of increasing permeability from 1 or 2 units to between 15 and 30 units, as measured by the AFS (American Foundries Society) permeability test. It is also provides a more economical use of the plaster. However, the inherent strength of the mold is reduced and if complex shapes are to be produced then flexible patterns, traditionally rubber, may be required [7].

The Antioch process has, as its special feature the requirement to process the molds in a steam autoclave. This produces a unique granular structure, which provides mold permeability. The molds produced by the Antioch process are more precise than foamed plaster molds and weaker than conventional plaster molds. However, this lower strength does not manifest itself until after mold production, which enables permanent patterns to be used [7].

The main advantages of plaster mold casting are listed as [7,8]:

- The ability to produce complex shapes.
- The ability to produce thin section castings.
- The excellent replication of pattern detail.
- The ability to produce castings, which are dimensionally accurate.
- The ability to produce castings with good surface finish.
- The minimization of residual stresses and distortion in castings.

The disadvantages of plaster mold casting are listed as [7,8]:

- Poor productivity due to lengthy processing procedures.
- The need for multiple patterns to improve molding productivity.
- The requirement for close control of the production process.

- The need for special procedures to overcome the problems of poor permeability.
- The possibility of impaired mechanical properties arising as a result of slow cooling of the casting.
- The mold materials are not reclaimable [5].

2.1.4. Materials Used in Mold Preparation

2.1.4.1. Gypsum. The principal materials used in the production of a mold are plaster and water. However, other materials are used to develop required mold characteristics and there are numbers of process variables which must be carefully controlled.

Gypsum plaster consists of a mixture of three related chemicals [4]:

- Calcium sulphate dehydrate ($CaSO4.2H2O$).
- Calcium sulphate hemi-hydrate ($CaSO4.0.5 H2O$).
- Calcium sulphate anhydrite ($CaSO4$).

The different proportions of these three chemicals determine the plaster's properties. Plaster of Paris is pure hemi–hydrate and it is produced by calcining the dehydrate at a temperature of 128 °C. The hemi-hydrate is available in two principal types, referred to as α and β. The α form is produced under pressure in a humid atmosphere, which results in an even crystalline structure. When the hemi-hydrate is produced at atmosphere pressure the water is given off as a steam, which disrupts the crystalline structure, resulting in the fragmentary crystals of β hemi-hydrate. The principal differences in their practical characteristics are that; β requires more water to produce a plaster and the resulting plaster and will set more quickly and be weaker [5].

The chemical change of calcination is reversible by simply adding water to the hemi-hydrate and this process is known as hydration. During hydration crystals of dehydrate are produced. Gypsum for foundry use is of two grades: gray and white. The gray product is less pure and less expensive than the white product. Gypsum (in containers) must be stored in a warm, dry area and should not be allowed to touch concrete floors or masonry walls. During periods of excessive humidity, it should be inspected regularly for evidence of contamination. To prevent overlong storage, containers should be marked with the date of receipt and the gypsum should be used in order of receipt [4,5].

2.1.4.2. Water. Water purity is important as the presence of organic materials causes variations in setting time and soluble salts can migrate to the mold surface during mold drying, causing efflorescence and hard spots which might impair surface smoothness. Water used for mixing the slurry should be of a quality suitable for human consumption. Temperature of the water at the time of combination with the dry ingredients to form the slurry is usually 15 °C to 25 °C (the temperature various among foundries). Water temperature has a significant effect on set time [4].

Variations in the water/plaster ratio will affect the mold strength and performance. It is essential that both materials should be weighed accurately before mixing. Although in the theory the volume of water required for hydration is only 18.6 per cent of the plaster volume, in practice considerably more water required to provide slurry fluidity. A typical mix ratio of plaster to water on a weight basis is 1:1.1 [9].

2.1.4.3. Plaster Additives. Proprietary plasters usually contain additives to enhance such mold properties as; green and dry strength, permeability and refractoriness. The additives used for this purposes include cement, clay silica, fiberglass and talc [4].

2.1.5. Patterns and Core Boxes

A wide range of pattern materials; plaster, wood, metal and plastic may be used for the plaster molding process [2,4].

2.1.5.1. Plaster Patterns. Plaster may be used for the pattern tooling as well as the mold material for short-run work.. That is by suitable formulation, a long semi set stage may be achieved during which it can be worked with strickles. The surface must be sealed to overcome the porosity of the dry plaster, however, the material is fragile, especially in thin sections. Its use is not advised for more than two or three molds because of the difficulties which arise in sealing the surface and parting the pattern from the mold [4].

2.1.5.2. Wood Patterns. Wood is relatively low-cost material and is readily carved. The surface must be very carefully sealed, however, and the finishing of the surface has to be carefully performed since even the normal wood grain can prevent withdrawal of the pattern from the plaster mold. Wood is inherently unstable, and should not be used when accuracy is imported [5].

Wood should only be considered for small quantity production or for cast to shape production of permanent patterns in metal or epoxy resin [5].

2.1.5.3. Plastic Patterns. Patterns produced using epoxy resin can be very accurate when properly made. However care must be taken to avoid distortion in heavy sections and thin sections may be brittle. These problems can be overcome by using metal parts for the thin sections and by lightening out the heavy sections [5].

2.1.5.4. Flexible Patterns. The use of flexible patterns is unique to the plaster process. Although frequently referred to as rubber patterns, they are actually produced of vinyl chloride or some similar like urethane. The material must completely recover after flexing. Flexible patterns may be either solid forms or shells of the flexible material backed with metal or plaster. Flexible patterns are usually produced by casting a thermoplastic material onto a negative of the finished pattern [4,5].

There is some danger of distortion of the flexible pattern due to the hydrostatic pressure of the plaster slurry while the mold is being made. The life of the pattern may be limited if it must be flexed too much to separate it from the mold. This type of pattern lends itself to the production of shapes with complex undercuts, an example being the production of the tread pattern in tire molds. The advantages of flexible urethanes may also be extended to core making [4].

2.1.5.5. Pattern Agents. Flexible patterns can be stripped from the mold without parting agents, but these materials are critical when rigid patterns are used because the plaster expands slightly onto the pattern while it is setting. A variety of oils, greases, and waxes may be used, with or without a solvent, and each foundry has its own formula. The addition of finely ground mica may be useful for deep draws. Whatever material is used as parting agent, it must be applied carefully and in sufficient quantity to ensure that the pattern strips from the mold. Excess parting agent causes accuracy and finish to detoriate, and there is a possibility of reaction with the molten metal when the mold is cast [4,5].

2.1.6. Flasks

Flasks are usually made of low carbon steel. They vary in size in accordance with the size of the pattern, the number of identical molds to be produced, and the number of patterns in a flask [4].

When the flask is to hold only one pattern half, especially when only a few mold required, a simple bottomless flask is placed on a moldboard, and the pattern half is positioned within on the board, ready to receive the slurry [4].

When many identical molds are required, especially when two or more patterns are placed in a single flask, a flask with a flat bottom that serves as a moldboard is used; the pattern halves are arranged on the flask bottom. Standardization of flask sizes is important in production operations, because this simplifies tooling especially when vacuum pouring is used [4,5].

2.1.7. Chills

Chills are often used in plaster molds, where they serve the same purposes as in other types of molds namely, they help to establish the required thermal gradients in the mold, and improve mechanical properties of the cast metal by increasing the cooling rate. Chills are placed around the pattern predetermined locations just before the slurry is poured. They are locked in the mold when the slurry sets and are thus less likely to be moved out of position than in sand molds [5].

2.1.8. Equipment for Drying the Molds

Plaster molds made by any process must be dried. The mold drying stage is critical in the production of the high quality molds and resultant castings. A forced air circulation oven with adequate ventilation and thermostatic control is recommended. Good circulation is necessary to ensure that even heating is obtained and the moisture-laden air must be vented and replaced with dryer air for the drying operation to be successful [7].

Most common drying temperatures range from 200 °C to 260 °C, but temperatures up to 500 °C have been used under carefully controlled conditions. It may be necessary to dry molds for periods of time of up to 72 hours. It is essential that the drying process removes both the free and combined water if gas defects in the casting to be avoided. This explains why a minimum temperature of 200 °C is recommended. Although drying can be accomplished more quickly at higher temperatures, these may cause shrinkage and cracking of the mold. An allotropic change, associated with a volume change, occurs in the plaster at a temperature around 380 °C. The choice of equipment depends largely on the temperature to be used and the number of the molds to be processed. For drying at 100 to 250 °C, either batch type or conveyor core ovens are satisfactory [6].

2.1.9. Gating Systems

For producing a few castings, or in attempting to establish an optimum gating system for a production run, common practice is to cut the sprues and the gates in the mold by hand after the plaster sets but before it dries. When the most appropriate gating practice is established for a job, the gating system should be made part of the pattern. Some foundries cut the gates off the first good casting, polish and silver plate them and use them as patterns for the gating systems for subsequent castings [9].

2.1.10. Metals Cast

Only non-ferrous metals are cast in plaster molds. Ferrous alloys are not suitable because most of them are poured at a temperature that would melt the calcium sulfate of which the molds are made. Calcium sulphate undergoes a phase transformation at 1195 °C and melts at 1450 °C [5].

2.1.10.1. Aluminum. All of the aluminum alloys that can be cast successfully in sand molds are suitable for casting in plaster molds. The more readily castable alloys, 43, 344, 355, and 356, are preferred [10].

2.1.10.2. Copper. Most of the coppers and copper alloys that can be cast successfully in sand molds can be cast in plaster molds. Copper alloys that contain more than about 5 per cent lead are not generally recommended for casting in plaster molds, because the higher-lead alloys react with some mold compositions, resulting in poor surfaces on the castings, defeating one of the objectives of plaster mold casting [5].

2.1.10.3. Magnesium Alloys. Magnesium alloys are not recommended for plaster mold casting. Reaction between magnesium alloys and the mold material is likely. In particular, magnesium alloys are will react with any free water that remains in the mold, and cause an explosion [4,5].

2.1.10.4. Zinc Alloys. Zinc alloys are frequently cast in plaster molds, most often for prototype castings. The die casting alloys AG40A and AC41A are often used, but a proprietary alloy whose coefficient of thermal expansion is very close to that of aluminum alloys is frequently cast. Master patterns appropriate for this zinc alloy or for aluminum can be made according to a single shrinkage rule [4].

Nominal compositions of the three zinc alloys mentioned here are given with Table 2.1:

Table 2.1. Zinc alloy compositions [4]

Component (%)	*Name of the Alloy*		
	AG40A	AC41A	Proprietary
Aluminum	4.1	4.1	12
Copper	0.1	1	0.8
Magnesium	0.035	0.055	0.02
Zinc	Remaining	Remaining	Remaining

2.2. Methods for Plaster Mold Casting

2.2.1. Conventional Plaster Mold Casting

Conventional plaster mold casting procedure is summarized with the following steps [11]:

- Mix dry ingredients.
- Add dry ingredients to water.
- Soak (2-4 minutes).
- Mix (2-5 minutes).
- Coat patterns (or core boxes).
- Pour slurry.
- Set at room temperature.
- Remove pattern.
- Dry molds.
- Assemble cores and mold halves.

2.2.1.1. Composition and Preparation for Dry Ingredients. Dry ingredients ready to mix with water are available as proprietary compositions. Compositions vary considerably, but the gypsum content is commonly (70 to 80 per cent), by weight of the dry mixture. Moldone talc is added to control several characteristics of the plaster. Small amounts of two or more other ingredients are usually added to control set time, mold strength and expansion [4].

In conventional process no special procedures or ingredients are used to increase the permeability of the mold. Lime, Portland cement, high strength gypsum cement, asbestos and terra alba are some of the additives that are most frequently used.

A typical composition setup for conventional plaster mold casting is given with the Table 2.2. Talc, cement, asbestos, cement and terra alba are selected as additives.

Table 2.2. Composition for conventional plaster mold casting [4]

Component	*Weight (g)*
Gypsum	100
White plaster	100
Talc	75
Cement	3
Asbestos	1
Terra alba	1

All dry ingredients must be thoroughly blended in a suitable mixer. Standard mixers are available. Most have several paddles mounted on a vertical shaft that rotate in a horizontal plane within a round-bottom container. Arrangement of paddles, shaft and container is not critical, as long as the mixer blends the dry ingredients thoroughly [4].

2.2.1.2. Mixing the Slurry. Equipment requirements for mixing the slurry are more precise. The principal components of a batch type mixer are a bucket and a propeller.

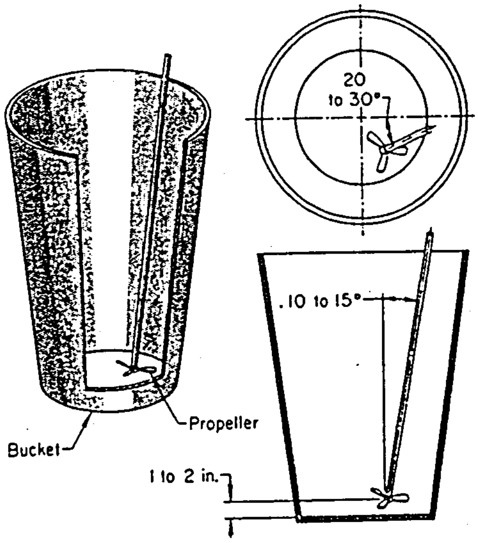


Figure 2.1. Bucket and propeller [4]

The bucket height should be equal to or slightly greater than the top diameter, and the bottom diameter should be approximately two thirds of the top diameter [4].

Continuous mixers are often used in production operations. They must have adequate capacity, a controllable positioning device, provision for minimizing air entrapment, provision for self cleaning and provision for controlling plaster to water ratio. The proportion of water to dry mixture may be varied however 1.5 parts water to 1 part dry mixture is commonly used as standard starting point. Once the exact proportions have been established, they should be rigidly adhered to, because the amount of water influences other features of the process such as set time and drying time and also influences mold dimensions. The water is weighed accurately and poured into the mixing bucket. The dry mixture is gradually added to the water. The combination is allowed to soak for 2 to 4 minutes [4,5].

The propeller is started and run as long as is required to cream the slurry. The slurry must be mixed sufficiently to prevent settling, but overmixing must be avoided. Overmixing will increase setting expansion and air entrapment. Undermixing will result in watering out and weak molds [12].

2.2.1.3. Preparing the Pattern. Because the slurry begins to set as soon as it is mixed, it must be poured over the pattern almost immediately and the pattern must be ready to receive the slurry [4].

Pattern preparation includes provision for matching the cope and drag to each other when the mold assembly made unless mold are to be left in the flasks for drying and assembly. Location pins are commonly used for matching of cope and drag. Positions of holes in the two mold halves must correspond, so that location pins, half in the cope and half in the drag mold sections, will hold the sections in correct alignment. A release agent must be applied to the pattern before the slurry is poured [4].

2.2.1.4. Pouring the Slurry. When the slurry is poured into the flask, the lip of the bucket should be kept close to the pattern. The slurry should be poured at a constant rate and made to flow over the pattern rather then to splash on it [4].

2.2.1.5. Set Time. Set time varies depending on the slurry composition and on some other factors, but 15 minute is usually the maximum set time. After the slurry has set the pattern and the flask are removed and the drying cycle is started as soon as is practical [4].

2.2.1.6. Drying the Molds. All conventional plaster molds must be dried enough to expel free water. In addition, it is usually desirable to remove the water of crystallization for a depth of at least 1.5 mm from the surface [13].

Oven drying should begin as soon as the mold is removed from the flask. Molds that have become partly dried by standing at room temperature are more susceptible to cracking and than those are oven-dried immediately after setting. If the molds must stand at room temperature for some time they should be covered with a damp cloth or stored in a humid atmosphere [5].

During drying, the mold should be uniformly supported on its edge or face. Common practice is to place the mold on a perforated flat metal plate, a rigid metal grid, or some other type of level support [5].

Time and temperature cycles used for drying conventional plaster molds vary widely among foundries. Temperature may vary from about 175 °C to 870 °C, and time from 45 minutes to 72 hr. Because furnaces are operated at high temperatures does not mean that all areas of the mold must reach this temperature range, but the interior of the mold must be at least 105°C to ensure removal of the free water [4,5].

Factors that govern the time and temperature of drying are; thickness of the mold sections total mass of the mold degree of drying required type of oven or furnace available, production schedule and required mold accuracy [4].

Production schedules influence selection of drying temperature. Often the length of time required for low-temperature drying is not compatible with other operations. A longer drying cycle means that a larger number of molds are processed at one time. Required accuracy also influences selection of drying temperature. Distortion and change of dimensions are greater when molds are dried in the high-temperature range. Mold shrinkage with low temperature drying is usually between 1 and 1.25 per cent; with high temperature drying shrinkage increases to 1.25 to 1.50 per cent. Most of this dimensional change can be compensated for when patterns made, if drying temperature has been established [4].

2.2.1.7. Mold Assembly. After the mold has been allowed to cool to approximately to room temperature, cores are placed in the drag half. Ceramic or plaster pins are placed in the holes provided in the drag half. The cope half is than lowered so that, pins protruding from the drag enter the machining pinholes in the cope as shown in the Figure 2.2 [4].

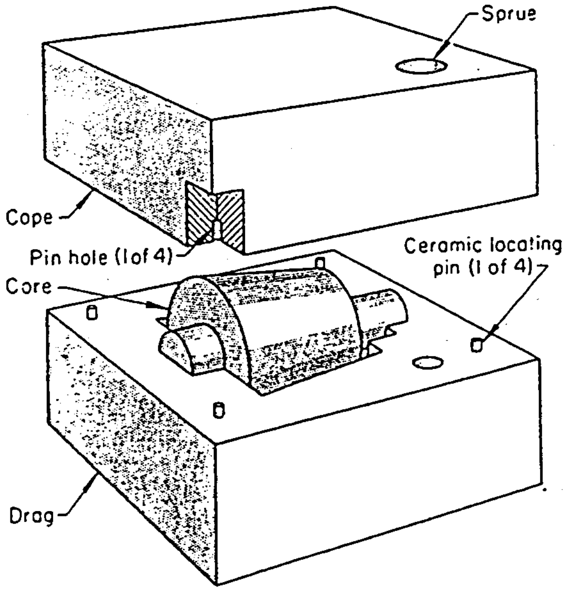


Figure 2.2. Plaster mold and core [4]

2.2.1.8. Preheating. Following assembly, the mold is ready for preheating. Some foundries preheat all conventional plaster molds to a pre-established temperature before pouring the metal. Other foundries preheat the molds only for specific applications for which preheating has proved advantageous. Preheating the mold can help to minimize defects or to obtain better replication of fine detail in the casting [4].

2.2.1.9. Pouring Practice. A dried plaster mold made by the conventional process has extremely low permeability about 1 to 2 AFS, compared with 80 and upward for sand molds. Because of this low permeability, either vacuum assist or pressure is usually required for pouring the molds. Simply gravity pouring is unusual. A typically setup for vacuum assist pouring is shown in Figure 2.3.

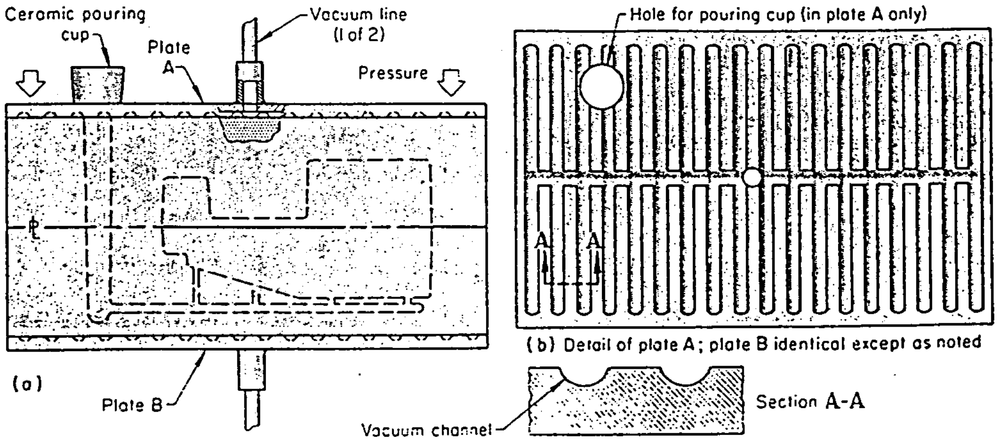


Figure 2.3. Vacuum assist in plaster mold casting [4]

Some foundries start the vacuum when pouring is started. Generally this technique is more effective when removing air from the mold, but the pull of the more complete vacuum creates turbulence in the molten metal as it enters the mold. Gating systems can be designed to lessen the turbulence [4].

<u>2.2.1.10. Shakeout and Cleaning</u>. Because of the insulating properties of the conventional plaster mold, solidification time is much longer than for a similar casting in a sand mold. Even small castings are seldom removed from their molds within an hour of pouring. Large castings require much more time before shakeout, often up to 48 hours [4].

The top portions of the mold where the plaster is the thickest can be carefully broken away to shorten the time between pouring and shakeout. Castings are usually removed from the molds by breaking the molds within hammers. The castings are then washed with water at high pressure, to remove most of the adhering mold and core material. Gating systems are removed by sawing and shearing [14].

Wet, blast abrasive cleaning is the most commonly used method for finish cleaning of the castings. Castings having fine detail usually require additional operation, which is performed manually as a bench operation [14].

2.2.2. Match Plate Pattern

Match plate patterns are cast by a particular adaptation of the conventional method of plaster molding. Changes in details of the conventional method ensure high accuracy and smooth surface finish, which are required of metal match plate patterns.

2.2.2.1. Sizes and Weights of Match Plate Patterns. A match plate pattern consists of a cope section and a drag section separated by a plate. These components are cast as an integral unit.

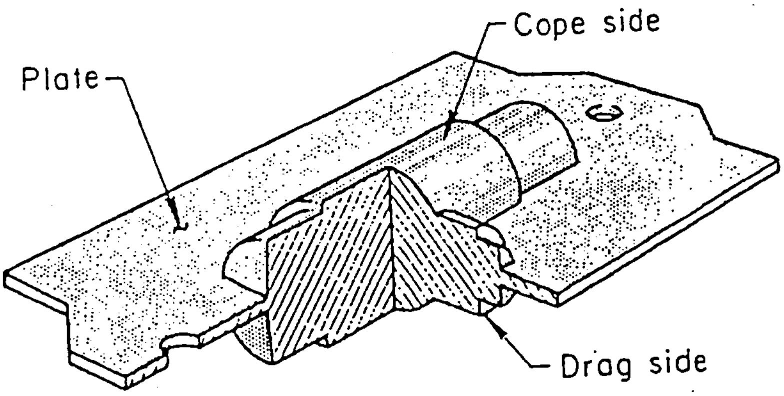


Figure 2.4. Match plate pattern [4]

Metal match-plate patterns can reach to 200 kg weigh. Match plate patterns seldom weigh more than 50 kg each and majority weighs from 10 to 20 kg [2,4].

A single plate may hold one pattern or many patterns. Thickness of the plate for small patterns having one pattern per plate is usually 1cm. The plate thickness increases as the size and the weight of the pattern increase. Plate thickness is also increased to provide adequate stiffness and bend resistance in designed involving a stepped parting line in separating cope and drag mold sections [4].

2.2.2.2. Mold Composition. Materials for molds for match plate patterns are available as proprietary dry mixtures ready for mixing with water. However some foundries prefer to make their own mixtures. A typical mixture of for match plate pattern molds is given in Table 2.3.

Table 2.3. Match plate pattern composition [4]

Ingredient	*Weight (g)*
White molding plaster	100
Moldane talc	41
Hydrated Lime	1,5
Portland Cement	0,5
Water	165 (for slurry)

2.2.2.3. Master Patterns. Master patterns are usually made of wood, but metal can also be used. Wood patterns must be coated to prevent absorption of the water from the slurry. Separate master patterns are made for the cope and the drag. The plate portion is developed by the technique described in this section under "mold assembly" rather than by means of a pattern. A release agent should be used for coating the pattern just before the slurry is poured [4,5].

2.2.2.4. Flasks. Bottomless boxes are used as flasks. They differ from flasks for conventional plaster mold casting in two respects. First standardization of flask size is seldom feasible in match plate pattern mold work, because pattern sizes vary widely. But standardization is less important, because molds are not required production quantities. Second, because the mold remains in the flask through the drying and metal pouring operations, provision for matching the cope and drag sections must be incorporated in the flask, rather than in the pattern as in conventional operations [4,5].

2.2.2.5. Mixing and Pouring The Slurry. Conventional plaster mold casting equipment and procedures are same with the match plate ones. Common practice is to make several vents in the mold with a nail or wire immediately after the slurry is poured. Vent holes traversing the entire mold section of dry molds provide openings for the escape of steam and other gases when metal is poured. Through vents in wet molds facilitate the separation of mold halves and the removal of patterns, by acting as channels for injection of compressed air for the system [4].

2.2.2.6. Set time for Match Plate Patterns. Slurry of the type defined in table 2.3 will set in 14 to 16 minutes. After the slurry sets the patterns are removed and the molds are dried [4].

2.2.2.7. Drying. Molds should be dried as soon as after the plaster sets. High temperature drying cannot be used for match plate molds because it results in unacceptable distortion and size change. Size and section thickness of the molds determine the length of time in the drying ovens. Permeability of a match plate mold is same as that of a conventional mold [4,5].

2.2.2.8. Mold Assembly. After the mold halves have reached the room temperature the cope and drag sections are matched as shown in Figure 2.5.

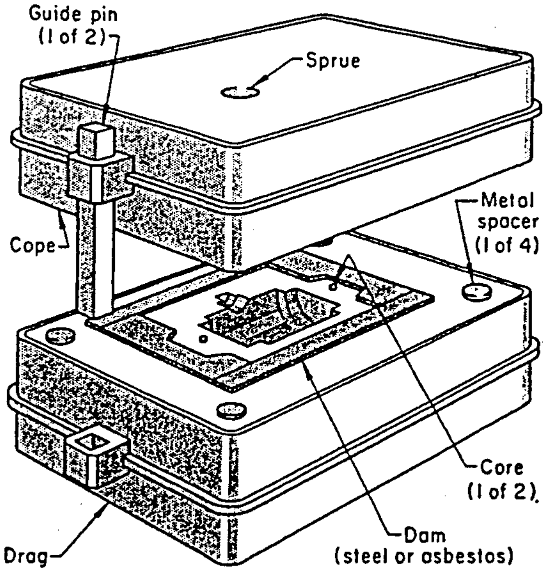


Figure 2.5. Assembly details of a match plate mold [4]

Assembly process is totally different than conventional plaster mold casting. Cores, if used, are positioned in the drag mold section. The cope section, aligned by guide pins is lowered onto the drag. It is than raised for a distance equal to the desired thickness of the plate. Metal spacers of this thickness are inserted at each corner, and dams of steel or asbestos are placed so as to form the desired outer contour of the plate. When the metal is poured, it flows outward in the space between the cope and drag sections and forms the plate portion of the match plate pattern [15,16].

2.2.2.9. Metals Used. Match plate patterns are cast from aluminum alloys and most frequent ones are 355 and 356. Ductility is important in making match plate patterns, because patterns often require straightening [4,10].

2.2.2.10' Pouring Practice. Because of the low permeability of a match plate mold, some assistance is required to fill the mold quickly and completely. Pressure assistance is used rather than vacuum, in part because pressure equipment is more adaptable to a variety of flask sizes than is vacuum equipment. The equipment for pressure casting is shown on Figure 2.6.

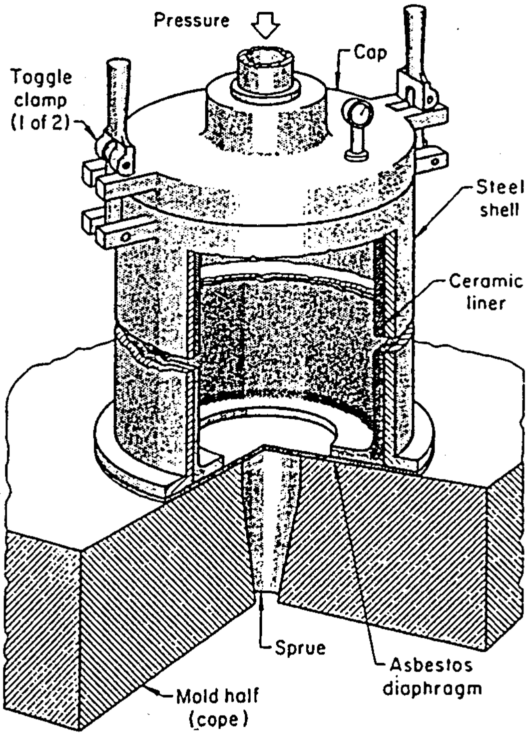


Figure 2.6. Cylinder for pouring a casting with pressure assist [4]

2.2.2.11. Shakeout. The time required between pouring and shakeout of match plate pattern castings will be same as conventional molds cast of similar size and weight. Shakeout procedures are generally same with the conventional procedures.

2.2.2.12. Straightening. The plan area of match plate castings is large in proportion to the cross sectional area, this will let castings to have distortion. When castings have an unacceptable amount of distortion, they must be straightened, which is commonly done by a skilled operator with the aid of an arbor press and a few simple press tools.

2.2.3. Antioch Process

The Antioch process was developed to overcome the principal limitations of the conventional plaster mold casting [17].

If undried molds are partially dehydrated and than allowed to rehydrate without being disturbed, gypsum crystals slowly recrystallize into granules about the size of sand grains, and the mold acquires a porous structure of relatively high permeability. Permeability is held within a range of 15 to 30 AFS, compared to 1 to 2 AFS for conventional plaster molds. Recrystallization does not take place at the surface of the mold, because not enough water is present. Therefore the surface remains smooth. In addition to the greater permeability developed by the dehydration-rehydration process, the molds produced have greater heat capacity than conventional plaster mold, because they are composed of approximately 50 per cent sand. Unlike conventional molds, Antioch process molds do not shrink [4,17].

2.2.3.1. Mold and Core Materials. Dry mixtures for Antioch-process molds and cores consist of silica sand, white molding plaster, moldene talc, and a small amount of material, such as Portland cement, for expansion control [5].

A typical composition for Antioch process is given with the Table 2.2. Selected additives are washed silica, moldone talc and Portland cement.

Table 2.4. Composition for Antioch process [4]

Ingredient	*Weight (g)*
Washed silica sand /AFS 50 typical	50
White molding plaster	42
Moldene talc	7,5
Portland cement	0,5
Water	54

2.2.3.2. Pattern Practice. Pattern practice is not generally different from that used for conventional plaster molding. Antioch process molds have exceptionally high green strength; extensive use is made of flexible rubber patterns with severe back drafts. Patterns must be coated with a release agent [4,5].

2.2.3.3. Flasks for Antioch Process. Flasks may be bottomless or they may have an integral bottom, depending mainly on the size of the casting and production quantity. Often, especially for making small, single-casting molds, the flask and the pattern are made as an integral unit [4].

2.2.3.4. Processing. Main difference between the conventional plaster mold casting and Antioch process is the dehydration and rehydration steps. The sequence of operations for producing Antioch process molds is given as the following:

- Mix dry ingredients.
- Add dry ingredients to water.
- Soak (1 to 3 min).
- Mix (2 to 4 min).
- Coat patterns (or core boxes).
- Pour slurry.
- Set at room temperature (15 to 20 minutes).

- Remove pattern.
- Dehydrate in autoclave (6 to 12 hour).
- Rehydrate in air (14 hr).
- Dry molds (or cores).
- Assemble cores and mold halves [4,5].

2.2.3.5. Mixing and Pouring. Mixing and pouring of the slurry over the patterns are accomplished by essentially the same equipment and procedure as described in conventional plaster mold casting [4].

2.2.3.6. Set Time. Set time for a slurry formulated from a composition such as that shown in Table 5 will be approximately 15 to 20 mins. Set time can be decreased by adding up terra alba and heating up the water. Temperature and humidity of the surrounding atmosphere have very little influence on set time although an atmospheric temperature of 20 °C to 25 °C is preferred [4,5].

2.2.3.7. Removing the Pattern. The pattern is removed as soon as the mixture sets. Usually the flask is removed at the same time as the pattern. However, large molds are sometimes allowed to remain in the flasks throughout subsequent mold processing and casting of the metal, because of their low dry strength. Antioch process molds sometimes need the support supplied by the flask [4].

2.2.3.8. Dehydration. The time between setting of the slurry and the beginning of the dehydration cycle is not extremely critical if steps are taken to prevent the mold from drying out. If the set molds are covered cloths, they can be held overnight, or sometimes over a weekend, without significant effect on subsequent dehydration. If the molds are placed in humidity cabinets, they can be stored for longer periods before dehydrating. However the dehydration cycle should begin soon after the pattern is removed if the mold cannot be kept moist. For dehydration, the molds are placed on suitable racks in a standard autoclave. The autoclave is sealed, and steam is admitted. The autoclave is operated with a steam pressure of 15 psi for 6 to 8 hours. For extremely large molds, it is operated for twelve hour. The autoclave is then opened and the molds are removed [4].

2.2.3.9. Rehydration. The mold is permitted to remain at room temperature for 14 hrs. After rehydration the mold is ready for drying.

2.2.3.10. Drying. Drying temperature ranges from 125 °C to 230 °C and drying time from 1 to 70 hr. Drying time depends mainly on the size of the mold and the temperature used. The center of the mold must reach at a temperature of at least 120 °C. This can be accomplished more quickly at an oven temperature of 230 °C than at 175 °C. Regardless of the cycle used, it is important that the same cycle be used for all molds of the same size. Only by close control of the cycle can maximum reproducibility be achieved [4,5].

2.2.3.11. Mold Assembly. Mold Assembly is essentially the same as described for conventional plaster molds. After the molds have cooled to room temperature cores are placed in the drag and the cope is placed over the drag-and-core assembly. Matching is done by means of locating pins. Even when molds are permitted to remain in their flasks, guide pins on the sides of the flasks are seldom used for matching [5].

2.2.3.12. Metals Cast. All of the aluminum alloys that can be cast in other types of plaster molds can be cast in Antioch process molds. Most copper base alloys can be cast in this process. Yellow brass is the copper alloy most often cast. The Antioch process is seldom used for alloys that must be poured at temperatures above about 1040 °C [4,18].

2.2.3.13. Pouring Practice. It is generally possible to pour castings in Antioch Process molds by gravity, using gating systems that are similar to those used for sand molding. Molds are usually at room temperature when pouring begins.

Vacuum assist can be applied when difficulty is encountered in replicating fine detail, or where thin sections have filled properly [5].

2.2.3.14. Shakeout and Cleaning. Time between pouring and shakeout is considerably less than for a conventional plaster mold because of the greater heat capacity of Antioch process [4].

2.2.4. Foamed Plaster Molds

The foamed plaster process offers greater mold permeability than can be obtained in conventional plaster molds. This can be obtained by adding a foaming agent such as alkyl aryl sulfonate, either to dry ingredients before mixing or to the liquid slurry, as a separately generated foam mix. A special method for mixing foams the slurry with many fine air bubbles, thereby decreasing the density and increasing the volume of the slurry [4].

2.2.4.1. Foamed Plaster Mold Characteristics. Foamed plaster molds have smooth surfaces with air cells just below the surface. During setting a subsequent drying of the molds these air cells become interconnected, thus permitting escaping of the gases as the metal is poured. Permeability of a foamed plaster depends mainly on the volume increase from the addition of air when the slurry is mixed. For most of the molds, a volume increase of 50 to 75 per cent is recommended. This increase usually results in a mold permeability of approximately 5 to 15 AFS (American Foundries Society Permeability Criteria), for dried molds; many foundries get 20 to 25 AFS permeability [4,14].

Table 2.5. Relationship between weight and permeability [4]

Volume Increase (%)	*Weight (g)*	*Permeability (AFS)*
0	90,8	1
50	60,6	5
6.1	57	8,5
68	53,8	11,5
76	49,4	16,5
100	46	30

The increase in permeability that accompanies an increase in volume of 75 per cent is the highest that can be allowed for most applications; with greater permeability, mold strength becomes unacceptably low. With great permeability it is possible to pour molds without assistance of pressure or vacuum [4].

Foamed plaster molds are less capable of absorbing heat than other types of plaster molds. This deficiency can be fixed by adding washed silica or zircon sand to the slurry. However the least absorption rate of foamed plaster molds cannot be expected to be much different from that of conventional or match plate plaster molds. The rate and direction of metal solidification can be controlled by chills, just as in other types of plaster mold casting [4].

2.2.4.2. Mold Compositions. Many users buy a proprietary formulation that contains the plaster and all other ingredients, including the foaming agent. Sand can be used to reduce the cost of the mold, or it can be used to increase the heat capacity. Sometimes both silica and zircon sands are used, for different sections of the mold, to take advantage of the different heat capacities of the two types of sand [4].

2.2.4.3. Equipment for Mixing. The mixer must be capable of beating air into the slurry and producing air cells. Large air cells are not permitted since they break under pressure molten metal, resulting in casting defects. Proper mixing can be accomplished with several types of mixers, regardless of type of mixer used the greater the power input, the finer the mold structure and smoother the mold surface of the mold. A convenient and suitable power unit is a simple vertical drill press that runs at 2500 rpm. A drill press permits the disk to be raised and lowered during the mixing cycle [4].

2.2.4.4. Mixing Procedures. Procedures vary with the slurry composition.. With some modification the following procedure can be applied to various slurry compositions. Time cycles given for the sample procedure are based on mixing 6 kg of dry mixture to 6 kg of water in a 30 lt. bucket using a rubber disk mixer [2].

The rubber disk is lowered to within 2 to 5 cm of bottom of the bucket. The dry mixture is poured into the bucket, and the water is added. After a soaking period of 30 seconds the mixer is started and run at 2500 rpm for 15 to 30 seconds, or until the dry ingredients and water are thoroughly mixed. At this point the rotating disk is raised high enough to throw air into the slurry, creating a vortex of the slurry mixture [2,4].

About half of the top area of the rotating disk should be visible as shown in Figure 2.7. Time of mixing depends on the desired volume increase. A volume increase of 70 per cent can usually be obtained for a 13 kg by mixing for 60 seconds. When the desired volume is obtained the rotating disk is lowered just below the surface of the slurry as shown in Figure 2.7 (b). Mixing is continued for another 60 seconds, or until the air bubbles are barely visible. Large air bubbles can be reduced in size by alternately raising and lowering the disk during this stage of mixing. With a little practice, an operator soon develops the skill to produce a foamed slurry that has air bubbles of desired size [4].

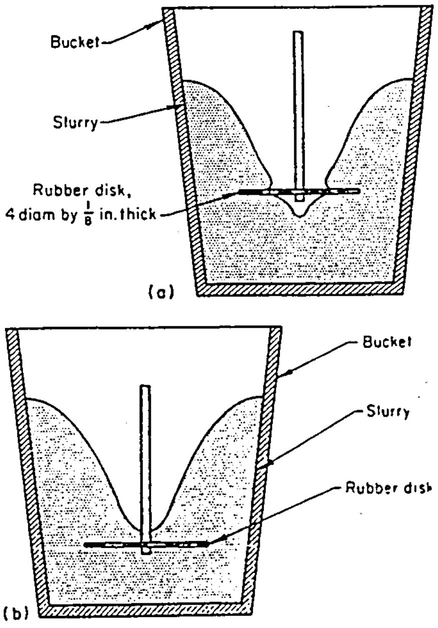


Figure 2.7. Mixing disk positioned for (a) throwing air into a foamed plaster slurry (b) final mixing of the slurry [4]

Pattern release agents are required as same as the other types of plaster mold castings.

2.2.4.5. Pouring the Slurry. The slurry should be poured over the pattern immediately after mixing. To obtain a smooth bubble free molding surface on a mold, it is desirable to vibrate the mold for a few seconds. Vibrating helps the large bubbles rise to exposed surface, away from the pattern. An alternate method for obtaining a smooth, bubble free surface is to brush or spray the pattern with a thin coat of the mixed slurry before pouring the plaster [4].

2.2.4.6. Set Time for Foamed Plaster Molds. Set time is usually 15 to 25 minutes. The pattern and mold can be separated when a clean finger no longer picks up material when the mold is lightly touched [4].

2.2.4.7. Removing The Pattern. Techniques for pattern removal are as same as the other types of plaster mold casting [4].

2.2.4.8. Drying. Temperatures needed to dry the molds vary between 175 °C to 260°C. Regardless of the oven temperature used, the center of the thickest section of any mold must reached 120 °C before it is considered dry [4].

2.2.4.9. Mold Assembly. As soon as the mold has cooled to room temperature the cores (if used) are assembled in the drag half. Usually the cope is matched with the drag by locating pins and pinholes [4].

2.2.4.10. Pouring Practice. Process is same as Antioch process. Most foamed plaster molds have sufficient permeability to permit pouring without vacuum or pressure assist.

2.2.4.11. Shakeout and Cleaning. More time must be allowed between pouring and shakeout than is needed for castings made in Antioch process molds because of the insulating properties of foamed plaster molds. The addition of sand (up to 25 per cent by weight) to the mold mixture helps to reduce this time interval, although at best the cooling time approaches that needed for conventional molds. Shakeout and cleaning methods are the same for castings made in foamed plaster molds as for those cast in conventional plaster molds [5].

3. DESIGN OF EXPERIMENTS

3.1. The Need for Design of Experiments

Experiments are carried out by investigators in all fields of study either to discover something about a particular process or to compare the effect of several conditions on some phenomena [19].

The role of a statistically designed experiment is to identify the most influential factors (vital few) associated with a particular characteristic and to define their relationships using analytical quantities. Since interactions between various factors are also defined, a single DOE can yield many revealing facts allowing the experimenters to quickly improve their process [19].

By the statistical design of experiments it is referred to the process of planning the experiment so that appropriate data will be collected, which may be analyzed by statistical methods resulting in valid and objective conclusions. Design of experiments allow for the simultaneous study of the effects that several factors may have on a process. When performing an experiment, varying the levels of the factors simultaneously rather than one at a time is efficient in terms of time and cost, and also allows for the study of interactions between the factors [19].

3.2. Basic Principals of Experiments

The statistical approach to experimental design is necessary if it is desired to have meaningful conclusion from the data. When the problem involves data that are subject to experimental errors, statistical methodology is the only objective approach to analysis. Thus, there are two aspects to any experimental problem: the design of experiment and the statistical analysis of data. These two subjects are closely related, since the method of analysis depends directly on the design employed [20].

The two basic principals of experimental design are replication and randomization. Replication is considered as the repetition of the basic experiment. Replication has two important properties. First it allows the experimenter to obtain an estimate of the experimental error. This estimate of error becomes a basic unit of measurement for determining whether observed differences in the data are really statistically different. Secondly, if the sample mean is used to estimate the effect of a factor in the experiment, then replication permits the experimenter to obtain a more precise estimate of this effect for if σ^2 is the variance of the data, and there are n replicates, then the variance of the sample mean is;

$$\sigma^2_y = \sigma^2 / n \qquad (3.1)$$

Randomization is the cornerstone underlying the use of statistical methods in experimental design. By randomization it is covered that both the allocation of the experimental material and the order in which the individual runs or trials of the experiment are to be performed are randomly determined. Statistical methods require that the observations (or errors) are independently distributed random variables. Randomization makes this assumption valid. By properly randomizing the experiment, it is also assisted in " averaging out" the effects of extraneous factors that may be present [20].

3.3. Designing an Experiment

In order to use the statistical approach to designing and analyzing an experiment, it is necessary that everyone involved in the experiment have a clear idea in advance of exactly what is to be studied, how the data is to be collected, and at least a qualitative understanding of how this data to be analyzed. A brief procedure is given with the following sections [19,20].

3.3.1. Recognition and Statement of the Problem

In practice it is often not simple to realize that a problem requiring experimentation that exists, and to develop a clear and generally accepted statement of this problem. A clear statement of the problem often contributes substantially to a better understanding of the phenomena and the final solution of the problem [21].

3.3.2. Choice of Factors and Levels

A factor is one of the controlled or uncontrolled inputs into a process whose influence upon a response is being studied in the experiment: The experimenter must select the independent variables or factors to be investigated in the experiment. The factors in an experiment can be either quantitative or qualitative. If they are quantitative, thought should be given as to how these factors are to be controlled at the desired values and measured. It is also mandatory to select the values or levels of the factors to be used in the experiment. These levels may be chosen specifically, or selected at random from the set of all possible factor levels [21].

3.3.3. Selection of a Response Variable

In choosing a response or dependent variable, the experimenter must be certain that the response to be measured really provides information about the problem under study. Thought must also be given to how the response will be measured, and the probable accuracy of those measurements [19].

3.3.4. Choice of Experimental Design

The experimenter must determine the difference in true response to detect, and the magnitude of the risks to tolerate so that an appropriate sample size (number of replicates) may be chosen. It is always necessary to maintain a balance between statistical accuracy and cost [19].

Most recommended experimental designs are both statistically efficient and economical, so that the experimenter's efforts to obtain statistical accuracy usually result in economic efficiency. A mathematical model for the experiment must also be proposed, so that the statistical analysis of the data may be performed [19,20].

3.3.5. Performing the Experiment.

This is the actual data collection process. Particular attention should be paid to randomization, measurement accuracy, and maintaining as uniform an experimental environment as possible [21].

3.3.6. Data Analysis

Statistical methods should be employed in analyzing the data from the experiment. Graphical methods are also frequently useful in the data analysis process [21].

3.3.7. Conclusions and Recommendations about the Experiments

Once the data has been analyzed, it can be obtained that conclusions or inferences about the results. The statistical inferences must be physically interpreted, and the practical significance of these findings must be made. These recommendations may include a further round of experiments, as experimentation is usually an iterative process, with one experiment answering some questions and simultaneously posing the others [20].

3.4. Factorial Experiments

Many experiments require a study of the effects of two or more factors. Factorial designs allow for the simultaneous study of the effects that several factors may have on a process [21].

3.4.1. Screening Designs

In many process development and manufacturing applications, the number of potential input variables (factors) is large. Screening (process characterization) is used to reduce the number of input variables by identifying the key input variables or process conditions that affect product quality. This reduction allows you to focus process improvement efforts on the few really important variables, or the vital few.

Screening may also suggest the best or optimal settings for these factors, and indicate whether or not curvature exists in the responses. Optimization experiments can then be done to determine the best settings and to define the nature of the curvature.

In industry, two-level full and fractional factorial designs, and Plackett-Burman designs are often used to screen for the really important factors that influence process output measures or product quality. These designs are useful for fitting first-order models (which detect linear effects), and can provide information on the existence of second-order effects (curvature) when the design includes center points. In addition, general full factorial designs may be used with small screening experiments [20].

3.4.2. Full Factorial Design

In a full factorial experiment, responses are measured at all combinations of the experimental factor levels. Each combination of factor levels represents the conditions at which a response measure will be taken. Each experimental condition is a called a "run" and each measure an "observation" [21]. The effect of a factor is defined to be change in response produced by a change in the level of the factor. This is frequently called a main effect because it refers to the primary factors of interest in the experiment.

Table 3.1. Factorial experiment [20]

		Factor B	
		B_1	B_2
Factor A	A_1	20	30
	A_2	40	52

3.4.2.1. General Analysis of Factorial Experiments. Analysis will be constructed on where there are a levels of factor A, b levels of factor B, c levels of factor C, and so on, arranged in a factorial experiment [20].

In general, there will be *n* total observations, if there are n replicates of the complete experiment. At least two replicates (n>1) in order to determine a sum of squares due to error if all possible interactions are included in the model.

If all factors in the experiment are fixed, it is easily to formulate and test hypotheses about the main effects and interactions.

For a fixed effects model, test statistics for each main effect and interaction may be constructed by dividing the corresponding mean square error. The number of degrees of freedom for any main effect is the number of levels of the factor minus one, and the number of degrees of freedom for an interaction is the product of the number of degrees of freedom associated with the individual components of the interaction [19-20].

For instance, the three factor analysis of variance model:

$$Y_{ijkl} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \varepsilon_{ijkl} \begin{cases} i = 1,2,\ldots\ldots\ldots, a \\ j = 1,2,\ldots\ldots\ldots, b \\ k = 1,2,\ldots\ldots\ldots, c \\ l = 1,2,\ldots\ldots\ldots, n \end{cases} \qquad (3.2)$$

Assuming that A,B and C are fixed, the analysis of variance table is shown in Table 3.1. The F test on main effects and interactions follow directly from the expected mean squares.

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{n} y_{ijkl}^{2} - \frac{y^{2}_{....}}{abcn} \qquad (3.3)$$

F values calculation for a three factors fixed model is shown with the Table 3.2. The analysis of variance is calculated with the ratio of expected mean squares for each factor with the error total.

Table 3.2. The analysis of variance table for the three factors fixed effects model [20]

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Expected Mean Squares	F_0
A	SS_A	$a-1$	MS_A	$\sigma^2 + \frac{bcn\sum\tau_i^2}{a-1}$	$F_0 = \frac{MS_A}{MS_E}$
B	SS_B	$b-1$	MS_B	$\sigma^2 + \frac{acn\sum\beta_j^2}{b-1}$	$F_0 = \frac{MS_B}{MS_E}$
C	SS_C	$c-1$	MS_C	$\sigma^2 + \frac{abn\sum\gamma_k^2}{c-1}$	$F_0 = \frac{MS_C}{MS_E}$
AB	SS_{AB}	$(a-1)(b-1)$	MS_{AB}	$\sigma^2 + \frac{cn\sum\sum(\tau\beta)_{ij}^2}{(a-1)(b-1)}$	$F_0 = \frac{MS_{AB}}{MS_E}$
AC	SS_{AC}	$(a-1)(c-1)$	MS_{AC}	$\sigma^2 + \frac{bn\sum\sum(\tau\gamma)_{ik}^2}{(a-1)(c-1)}$	$F_0 = \frac{MS_{AC}}{MS_E}$
BC	SS_{BC}	$(b-1)(c-1)$	MS_{BC}	$\sigma^2 + \frac{an\sum\sum(\beta\gamma)_{jk}^2}{(b-1)(c-1)}$	$F_0 = \frac{MS_{BC}}{MS_E}$
ABC	SS_{ABC}	$(a-1)(b-1)(c-1)$	MS_{ABC}	$\sigma^2 + \frac{n\sum\sum\sum(\tau\beta\gamma)_{ijk}^2}{(a-1)(b-1)(c-1)}$	$F_0 = \frac{MS_{ABC}}{MS_E}$
Error	SS_E	$abc(n-1)$	MS_E	σ^2	
Total	SS_T	$abcn-1$			

The sum of squares for the main effects are from the totals for factors $A(y_{i....})$, $B(y_{.j...})$, $C(y_{..k.})$ as follows;

$$SS_A = \sum_{i=1}^{a}\frac{y_{i\cdots}^2}{bcn} - \frac{y_{\cdots}^2}{abcn} \tag{3.4}$$

$$SS_B = \sum_{j=1}^{b}\frac{y_{.j..}^2}{acn} - \frac{y_{\cdots}^2}{abcn} \tag{3.5}$$

$$SSc = \sum_{k=1}^{c}\frac{y_{..k.}^2}{abn} - \frac{y_{\cdots}^2}{abcn} \tag{3.6}$$

To compute the two factor interaction sums of squares, the totals for the Ax B, Ax C, and B x C cells are needed. It is frequently helpful to collapse the original data table into three two-way tables in order to compute these quantities [19,20].

The sum of squares is found from;

$$SS_{AB} = \sum_{i=1}^{a}\sum_{j=1}^{b} \frac{y_{ij\cdot\cdot}^{2}}{cn} - \frac{y^{2}_{\cdot\cdot\cdot\cdot}}{abcn} - SS_{A} - SS_{B} \tag{3.7}$$

$$SS_{AB} = SS_{subtotals(AB)} - SS_{A} - SS_{B} \tag{3.8}$$

$$SS_{AC} = \sum_{i=1}^{a}\sum_{k=1}^{c} \frac{y_{i\cdot k\cdot}^{2}}{bn} - \frac{y^{2}_{\cdot\cdot\cdot\cdot}}{abcn} - SS_{A} - SS_{C} \tag{3.9}$$

$$SS_{AC} = SS_{subtotals(AC)} - SS_{A} - SS_{C} \tag{3.10}$$

$$SS_{BC} = \sum_{j=1}^{b}\sum_{k=1}^{c} \frac{y^{2}_{\cdot jk\cdot}}{an} - \frac{y^{2}_{\cdot\cdot\cdot\cdot}}{abcn} - SS_{B} - SS_{C} \tag{3.11}$$

$$SS_{BC} = SS_{subtotals(BC)} - SS_{B} - SS_{C} \tag{3.12}$$

The two factor sub-totals sums of squares are found from the totals in each two-way table. The three factor interaction sum of squares is computed from the three-way cell totals $\{\gamma_{ijk}\}$ as;

$$SS_{ABC} = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c} \frac{y^{2}_{ijk\cdot}}{n} - \frac{y^{2}_{\cdot\cdot\cdot\cdot}}{abcn} - SS_{A} - SS_{B} - SS_{C} - SS_{AB} - SS_{AC} - SS_{BC} \tag{3.13}$$

$$SS_{ABC} = SS_{subtotals(ABC)} - SS_{A} - SS_{B} - SS_{C} - SS_{AB} - SS_{AC} - SS_{BC} \tag{3.14}$$

The error sum of squares may be found by subtracting the sum of squares for each main effect and interaction from the total sum of the squares; or by;

$$SS_{E} = SS_{T} - SS_{subtotal(ABC)} \tag{3.15}$$

It has been indicated that if all the factors in a factorial experiment are fixed, then test statistic construction is straightforward. The statistic for testing any main effect or interaction is always formed by dividing the mean square for the main effect or the interaction by mean square error. However, if the factorial experiment involves a random or mixed model, then test statistic construction is not immediately obvious. In theses cases, expected mean squares should be examined to determine the correct test, which will not be explained in this thesis study [20,21].

3.4.2.2. Fractional Replications. As the number of factors in a 2^k or 3^k factorial design increases, the number of runs required for a complete replicate of the design rapidly outgrows the resources of most experimenters. For instance, the 3^6 factorial requires 243 runs, and only 12 of the 242 degrees of freedom correspond to main effects. If the experimenter can reasonably assume that certain high order interactions are negligible, then information on main effects and low-order interactions may be obtained by running only a fraction of the complete factorial experiment. A major use of fractional factorials is in screening experiments. In this survey, 2^k series will be summarized as fractional factorial designs [20].

3.4.2.3. Half Fraction of the 2^k Experiment. In a three factor, two level experiment, there are 8 runs needed to be performed for the full fractional experiment. For some reasons (cost, time, labor etc.) experimenter may choose to run a half fractional experiment which consists of only 4 runs. The table of plus and minus signs for the 2^3 design is shown in Table 3.3. If it is selected as four treatment combinations a,b,c and abc as the one-half fraction, the notation will be;

Table 3.3. Notation for the fractional design [20]

Notation 1	*Notation 2*
a	+ - -
b	- + -
c	- - +
abc	+ + +

It may be noticed out that selected half fractional design is formed by only those treatment combinations that yield a plus on the ABC effect. Thus ABC is called the generator of this particular fraction. Furthermore the identity element is always plus;

$$I = ABC \tag{3.16}$$

is the defining relation for the design [20].

Table 3.4. Plus and minus table for the 2^3 factorial design [20]

	Factorial Effect							
Treatment Combination	***I***	***A***	***B***	***C***	***AB***	***AC***	***BC***	***ABC***
a	+	+	-	-	-	-	+	+
b	+	-	+	-	-	+	-	+
c	+	-	-	+	+	-	-	+
abc	+	+	+	+	+	+	+	+
ab	+	+	+	-	+	-	-	-
ac	+	+	-	+	-	+	-	-
bc	+	-	+	+	-	-	+	-
(1)	+	-	-	-	+	+	+	-

The treatment combinations in this fractional design yield three degrees of freedom that may be used to estimate the main effects. The estimates of the main effects as;

$$A = ½ [a- b- c + abc] \tag{3.17}$$

$$B = ½ [-a + b- c + abc] \tag{3.18}$$

$$C = ½ [-a - b + c + abc] \tag{3.19}$$

It is also easy to verify from the Table 3.3 that the estimates of the two factor interactions are;

$$BC = \frac{1}{2}[a - b - c + abc] \tag{3.20}$$

$$AC = \frac{1}{2}[-a + b - c + abc] \tag{3.21}$$

$$AB = \frac{1}{2}[-a - b + c + abc] \tag{3.22}$$

From the given equations it can be concluded that it is impossible to differentiate between A and BC, B and AC, and C and AB. Two or more effects that have this property are called aliases.

The alias structure for this design may be determined by using the defining equation (I= ABC).

Multiplying any effect by the defining relation modulus 2 yields the aliases for that effect [20].

$$A \,.\, I = A \,.\, ABC \tag{3.23}$$

$$A = A^2BC = BC \tag{3.24}$$

Table 3.5. Alternative half fraction notations [20]

Notation 1	*Notation 2*
(1)	- - -
ab	+ + -
ac	+ - +
bc	- + +

The defining relation,

$$I = -ABC \tag{3.25}$$

The aliases are A = -BC, B = -AC, and C= -AB. The fraction associated with I = ABC is called the principal fraction.

It is meaningful to note that if one factor proves unimportant, a full factorial design may be obtained from the remaining two factors. A projection may be considered as follows;

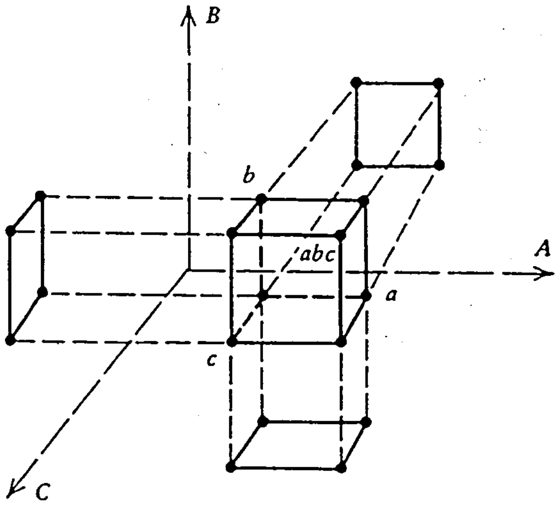


Figure 3.1. Projection of a 2^{3-1} design into three 2^2 designs [20]

3.4.2.4. Box and Honor Fractional Design. Fractional designs according to resolution are classified by Box and Honor as given below:

- Resolution III designs are designs in which no main effects is aliases with any other main effect, but main effects are aliased with two-factor interactions and two factor interactions are aliased with each other.

- Resolution IV design are designs in which no main effect is aliased any other main effect or two factor interaction, but two factor interactions are aliased with other.

- Resolution V designs are designs in which no main effect or two factor interaction is aliased with any other main effect or two – factor interaction, but two factor interactions are aliased with three factor interactions [19,20].

3.5. Taguchi Methodology

The appeal of the Taguchi method lies in its ease of use and its emphasis on reducing variability to give more economical production. The Taguchi method and other fractional factorial experiments are very similar. Taguchi simplified design of experiments by developing a set of fractional factorial designs that can be used as templates, which greatly streamlines the experimental process [3].

3.5.1. Loss Function

From an engineering standpoint, the losses of concern are those caused by a product's functional characteristic deviating from its desired target value. In Taguchi's philosophy, loss occurs not only when the product is outside of specifications, but also when the product falls within specifications. Further, it may be reasonable to believe that the loss continually increases as the product deviates further from the target value as indicated by the quadratic loss function in Figure 3.2 [22].

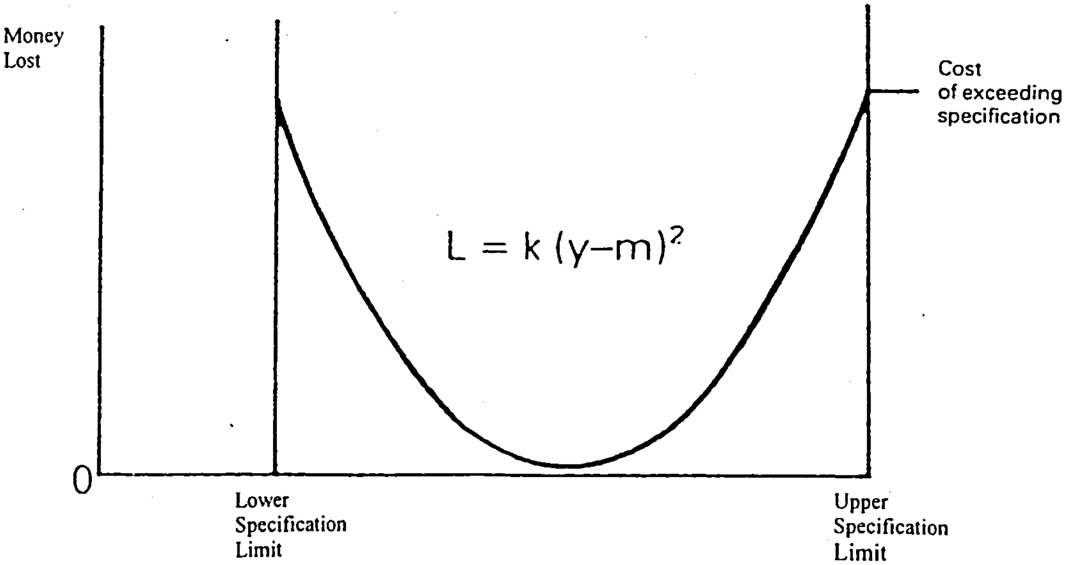


Figure 3.2. Loss function [22]

While a loss function may take on many different forms, Taguchi has found that the simple quadratic function approximates the behavior of loss in many instances. For the case where the quality characteristic of interest is to be maximized or minimized, the loss function may become a half parabola. In any event, belief in the loss function promotes efforts to reduce continually the variation in the product's functional characteristic. Loss function can be reviewed as:

$$\$L = k(y - m)^2 \tag{3.26}$$

3.5.2. Performance Variations

Variations from desired performance values cause loss of quality. The ability to control performance variations comes from the knowledge of the size of variation. The deviation of the process is measured via process capability studies. The effect of the ratio of the functional specification to the process spread will show if the process needs to be revised [23].

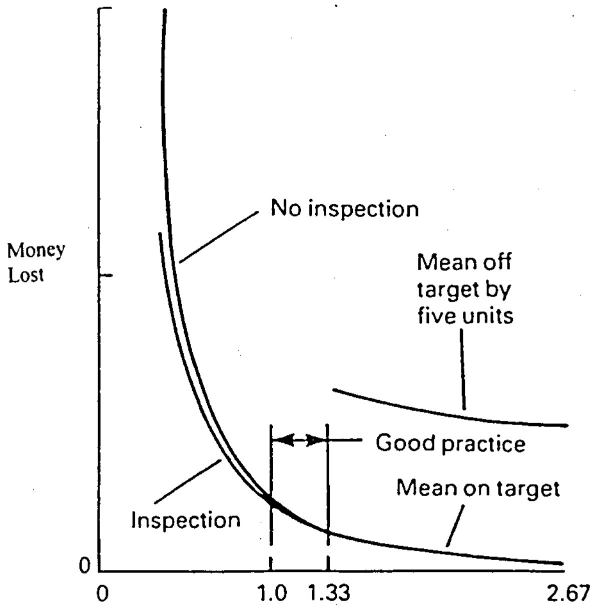


Figure 3.3. Effect of standard deviation on quality loss [23]

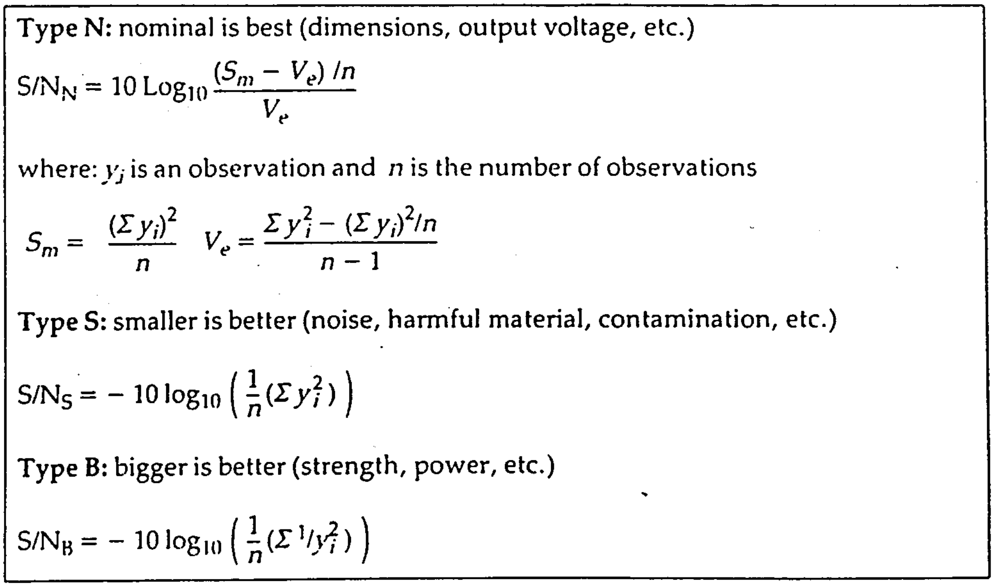
3.5.3. Controllable vs. Noise Factors

To minimize loss, one is faced with the task of producing the product at optimal levels with minimal variation in its functional characteristics. These are classified as controllable and noise factors. Controllable factors are those factors, which can be easily controlled such as choice of material, cycle time or temperature. Noise factors on the other hand are those variables, which are either difficult, or impossible, or expensive to control. Noise factors, in general, are responsible for causing a product's functional characteristic to deviate from its target value. In Taguchi methodology it is preferable to select values for the controllable factors such that the product or process is least sensitive to changes in noise factors. That is, instead of finding and eliminating causes, as the causes are often noise factors, the intent is to remove or reduce the impact of the causes. The tool which is employed to achieve the robustness against noise factors and reduced cost is called parameter design. Parameter design, Taguchi style, involves experimental design techniques utilizing orthogonal arrays and (S/N) ratio [22,23].

3.5.4. Signal to Noise Ratio

Response variable in the experiment (performance characteristic) needs to be controlled at both mean level and the variation around the mean. Therefore, it would be convenient to use an objective measure that combines both of these parameters in one metric. Table 3.6 gives such a figure of merit, which Taguchi has called the signal to noise ratio (S/N) for various types of performance characteristic. In its elemental form, (S/N) is simply the ratio of the mean to the standard deviation. In general S/N will always be maximized to achieve a robust product design. Taguchi developed over 70 distinct (S/N) metrics. The most used three types of ratios are also given in Table 3.6. [22].

Table 3.6. S/N ratios of Taguchi methodology [22]



Type N: nominal is best (dimensions, output voltage, etc.)

$$S/N_N = 10\,\mathrm{Log}_{10} \frac{(S_m - V_e)\,/n}{V_e}$$

where: y_i is an observation and n is the number of observations

$$S_m = \frac{(\Sigma y_i)^2}{n} \quad V_e = \frac{\Sigma y_i^2 - (\Sigma y_i)^2/n}{n-1}$$

Type S: smaller is better (noise, harmful material, contamination, etc.)

$$S/N_S = -\,10\log_{10}\left(\frac{1}{n}(\Sigma y_i^2)\right)$$

Type B: bigger is better (strength, power, etc.)

$$S/N_B = -\,10\log_{10}\left(\frac{1}{n}(\Sigma\, {}^1\!/y_i^2)\right)$$

3.5.5. Parameter Design

The strategy in parameter design is to recognize controllable factors and noise factors and to treat them separately. The search for interactions among controllable factors is de-emphasized, while the discovery of interactions between controllable factors and noise factors is the key to achieving robustness against noise. As long as the noise factors are changed in a balanced fashion during experimentation, then preferred parameter values can be determined through analysis of an appropriate S/N ratio [23].

3.5.6. Orthogonal Arrays and Interaction Effects

Most statistical experimental designs are based on matrices where the columns are assigned to the factors and the rows list the experimental conditions for each trial. The matrices used in designed experiments are orthogonal arrays because the factor levels are balanced, allowing the factor effects on the response to be separated from each other. However, they are normally called orthogonal arrays only in the Taguchi method [22,23].

The simplest orthogonal array is used in the full factorial experiment. All of the main and interaction effects are orthogonal to each other in this design so that they can be separated from each other and evaluated. However, the design requires many trials, which often impedes experimental replication, since resources are always limited [23].

The orthogonal arrays used in full factorial experiments use only part of the factor level combinations to estimate the main effects and some interactions. In these designs, the main effects and some of the lower order interaction effects are orthogonal to each other, which allows these effects to be evaluated without bias. The higher-level interactions are confounded and aliased with each other. Confounding occurs when the effects of two or more factors cannot be separated [23].

A typical orthogonal array is given with the Table 3.7. Four factor and 3 level for each factor are selected as the design of experiment parameters.

Table 3.7. The L9 orthogonal array [23]

TRIAL	*A*	*B*	*C*	*D*	*RESPONSE*
1	1	1	1	1	y1
2	1	2	2	2	y2
3	1	3	3	3	y3
4	2	1	2	3	y4
5	2	2	3	1	y5
6	2	3	1	2	y6
7	3	1	3	2	y7
8	3	2	1	3	y8
9	3	3	2	1	y9

The Taguchi methodology uses pairwise orthogonal arrays that are usually of resolution III so that the main effects are not aliased with each other but are aliased with the interactions. This results the smallest experimental array to determine the main effects. However, it is not possible to determine the interactions.

The arrays are also saturated, since the same number of effects is being evaluated as the number of experimental trials being conducted. Therefore, no degrees of freedom are available to estimate the error variance, since all the available information is being used to evaluate the main effect. It is possible to assign one or more columns in the orthogonal array to error variance analysis so that fewer factor effects are determined, but this results in less efficient use of the trials. In addition, the ability to replicate the small number of trials allows information to be obtained about the noises present in the system, which might not be possible with designs that require more trials. The Taguchi method is often criticized for its apparent inability to handle factor interactions. The normal assumption in the methodology is that the interactions can be ignored and that only the main effects are significant [22,23].

3.5.7. Typical Taguchi Method Experimental Procedure

The first step is to define the question that is being asked. It is very important to include all of the properties and parameters of interest at this stage of the experimental process, so that significant properties and parameters are not forgotten. Therefore, any information known about the process is then used to decide which of these properties and parameters are probably most significant [23].

Once the properties and parameters to be investigated have been chosen, the next step of the Taguchi method is to define the experiment. This is done by selecting an orthogonal array that uses an appropriate number of factors and levels to investigate the chosen parameters. Table 3.7. shows common orthogonal arrays to be used.

Table 3.8. Orthogonal arrays [23]

Name	*Parameters*	*Levels*	*Combinations Possible*	*Required Trials*
L4	3	2	8	4
L8	7	2	128	8
L9	4	3	81	9
L12	11	2	2048	12
L16	15	2	32768	16
L'16	5	4	1024	16

The factor levels should be chosen so that they cover a wide range of the possible parameter settings, to prevent the exclusion of the optimum combination of factor settings. However impossible or unfeasible factor levels should be avoided to be chosen. After the factors and levels are selected, the factors are assigned to the columns of the array. This can be either randomly if there is little difficulty in changing the factor values or it can be done so that the most difficult factor to change is assigned to the first column, which is changed infrequently. Finally the levels of each factor assigned. Once the factors and levels have been assigned, the experiment is conducted with repetition of each trial, if possible [23].

Analysis of the results can be performed on a simple spreadsheet. Regardless of whether the actual response, y or the (S/N) ratio, is to be optimized, the effect of each factor at each level is found by subtracting the average overall response, from the average response for the trials where the factor has been set to the level of interest [22]. This is illustrated for factor C at level 3 in the L9 array in table 3.6, which is known as effect c_3.

$$c_3 = [(y_3 - y_5 - y_7) / 3] - \bar{y} \tag{3.27}$$

One consequence of this formulation is that all of the effects for a factor must sum to zero. The magnitude of the effect is simply the difference between the largest and smallest effect for the factor. The predicted response for any combination of factor levels can be found by adding the effects of each factor at the desired level to the mean response. Selecting the smallest effect for each factor will predict a minimum response, while selecting the largest effect of each factor will attempt to maximize the response [22].

3.6. A Useful Industrial Waste Product: Fly ash

Fly ash is a sub product of coal-fired power plants. More than eleven million tons of fly ash is produced in the coal-fired power plants in Turkey every year. Fly ash is utilized in many areas of engineering in industrialized countries and in this study Soma fly ash as an additive to plaster mold casting is examined [24,25].

Table 3.9. Soma fly ash chemical and physical properties [25]

Component	*Weight (%)*
SiO2	26.50
Fe2O3	1.89
A12O3	51.40
CaO	14.01
MgO	1.95
SO3	2.87
Loss Of Ignition	0.70
Residue	0.63
Humidity	0.14
Density (g/cm^3)	2.62

4. EXPERIMENTAL WORK

4.1. Designing of the Current Experiments: Taguchi Roadmap

4.1.1. Defining the Problem and Selecting the Parameters

The purpose of first set of experiments is to identify the effects on setting time and the surface smoothness of the molds in plaster mold casting.

Whether it is used for prototyping or mass production, in plaster mold casting, the long cycle time for producing a single mold is the main disadvantage. Therefore; setting time of the plaster molds is selected to be minimized. It should also be considered that while decreasing the setting time, the surface quality should be under control at the same time. As the first step of roadmap, setting time and surface roughness is selected as parameters (responses) for the Taguchi experiment sets.

4.1.2. Defining the Factors and Levels

Temperature, mixture composition (additives), water temperature, mixer type, mixing time, mixing angle are considered as possible factors which may effect the responses. However, mixing time, additives and water temperature are selected as experimental factors since they are the most feasible ones to be controlled. For an optimizing study, three levels from each factor are determined.

Table 4.1. Selected factors and levels for Taguchi experiments

Factor Name	*Level 1*	*Level 2*	*Level 3*
Water Temperature	15 °C	30 °C	45 °C
Additive Compositions	10-T	20-T	30-T
Mixing Time	30 sec	60 sec	90 sec

10-T, 20-T and 30-T are three different types of mixture compositions. The ingredients for all these three types of additive compositions are given with the Table 4.3.

4.1.3. Selecting an Orthogonal Array

With three factors and three levels each, in total, 27 runs are needed to perform a full factorial experiment without any replication. Instead, using the Taguchi's approach and by choosing a L9 orthogonal array only 9 runs are needed to analyze the main effects with the assumption of higher level interactions can not be calculated [26]. Every run in this experiment is replicated once to overview the variances in the process.

Table 4.2. Standard and applied L9 orthogonal arrays [26]

A	B	C
1	1	1
1	2	2
1	3	3
2	1	2
2	2	3
2	3	1
3	1	3
3	2	1
3	3	2

temp	**time**	**additive**
15	0,5	10
15	1	20
15	1,5	30
30	0,5	20
30	1	30
30	1,5	10
45	0,5	30
45	1	10
45	1,5	20

4.2. Experimental Procedure

4.2.1. Preparing the Pattern and the Flask

An actual front engine cover of a diesel engine is chosen as the metal model of the desired geometry and used as the pattern in the plaster mold casting. A painted wood flask is used as the flask. Flask dimensions are 150x150x60 mm. The technical drawing of the front engine cover to be cast is given with figure 4.1. Flask used in the experiments is also shown in Figure 4.2.

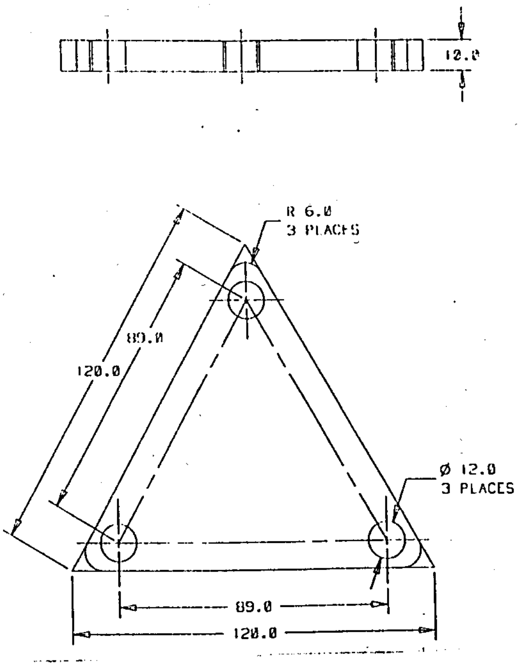


Figure 4.1. Front engine cover pattern

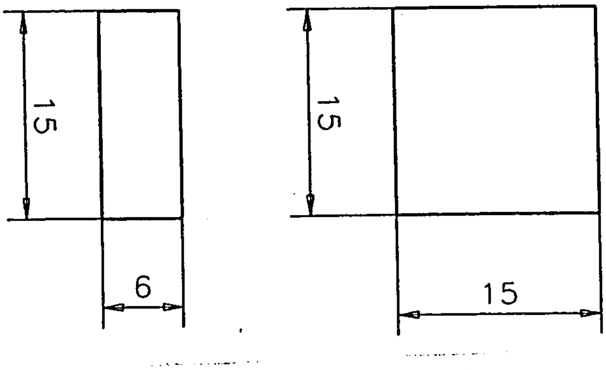


Figure 4.2. Flask

4.2.2. Mold Material Composition

It has been determined that additive to water to plaster mixture was chosen as a factor in the experiment. Fly ash is used as an additive in this set of experiments; therefore 3 different levels of fly ash addition are notated as 10-T, 20-T and 30-T type mixtures.

Table 4.3. Mixture compositions used in Taguchi analysis trials

Weight for each factor (g) / Notation	**10-T**	**20-T**	**30-T**
Water	480	480	480
Plaster	300	275	250
Fly ash	0	25	50

General plaster types available for plaster mold casting are given in table 4.4. In the present study industrial plaster is used for preparing the slurries.

Table 4.4. Plaster properties

Types Of Plaster	*Set Time (minutes)*	*Dry Composition Strength (kPa)*	*Drying Time and Temperature (h/°C)*	*Dry Density (kg/m^3)*
Industrial	27-37	8275	12 – 130	1560
Molding	27-37	13790	12 – 130	1585
White	27-37	13790	12 – 130	1585
Casting	27-37	8275	12 - 130	1600

Fly ash used in experiments is obtained from Soma coal-fired power plant. Average size of Soma fly ash is 24 µm. Other chemical and physical properties of the fly ash is available in Table 3.9.

4.2.3. Mixer Type

The mixer for mixing the slurry is shown in Figure 4.3. A fixing apparatus (also shown in Figure 4.3.) is used to fix the mixer position.On every run for experiments same mixer and bucket positions are kept to minimize the variation in mixing process. Mixing angle and mixer position inside the bucket are the most critical parameters for the slurry preparation process. Therefore, the fixing apparatus has a major role on keeping the process stable during the mixing process, until the slurry preparation finishes.

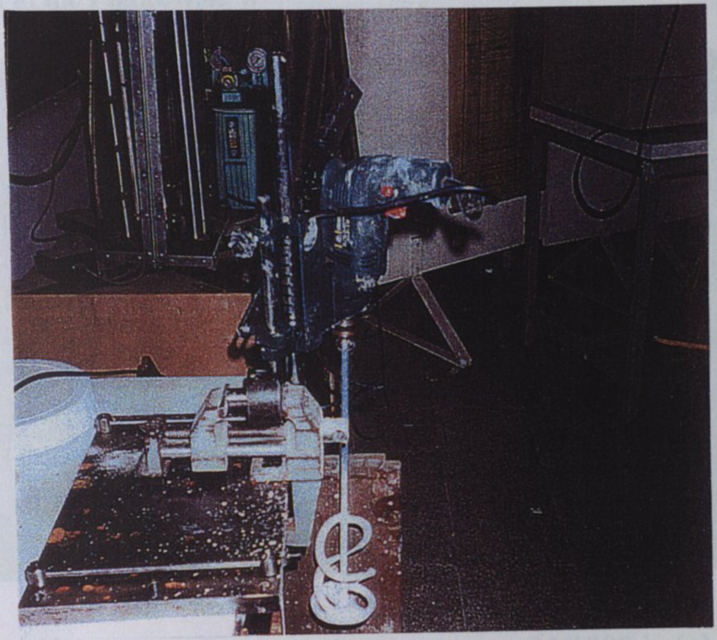


Figure 4.3. Mixer with the fixing apparatus

The characteristics of the mixer is given in Table 4.5.

Table 4.5. The characteristics of the mixer used in slurry preparation

Power	0.25 kW
Speed	1500 rpm
Blade Type	Helical
Blade Material	Galvanized Steel
Blade Diameter	90 mm

4.2.4. Performing the runs

For every single run, ingredients are prepared with a sensitive balance, which has the accuracy of 1 g in 1 kg. Then, ingredients are added to water, after soaking for 10 seconds the components are mixed immediately until the determined mixing time exists.

Slurry is poured on the pattern as soon as the mixing process is finished. A pattern releasing agent is used for easy disassemble operation. The electric balance used in experiments is shown in the Figure 4.4.

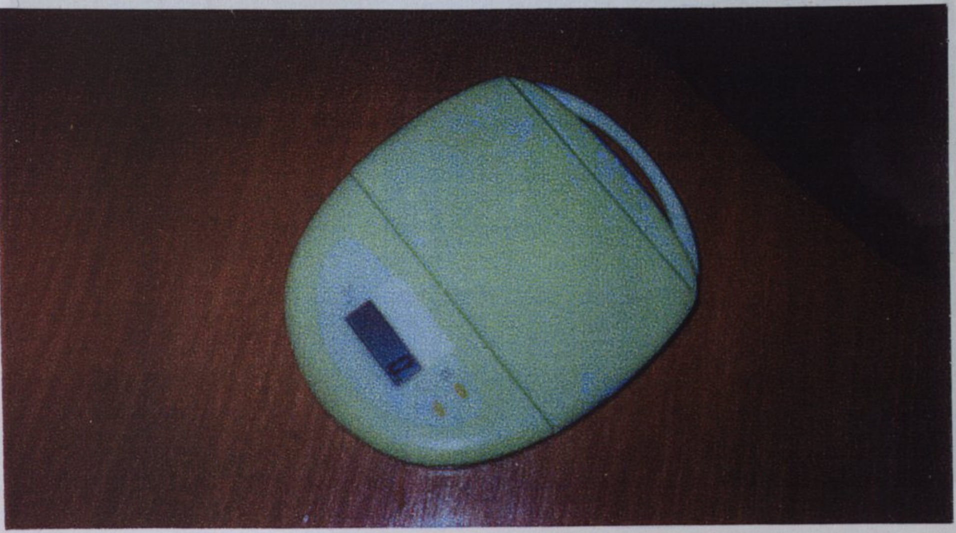


Figure 4.4. Electric balance with the accuracy of 1/1000 in (g)

Set time is recorded as from the start of mixing process until the mold sets. Figure 4.4, 4.5 and 4.6 show the 18 molds produced in the laboratory. The replications mean that every run is repeated once for all 9 settings. These replications are used for obtaining the process variances [23].

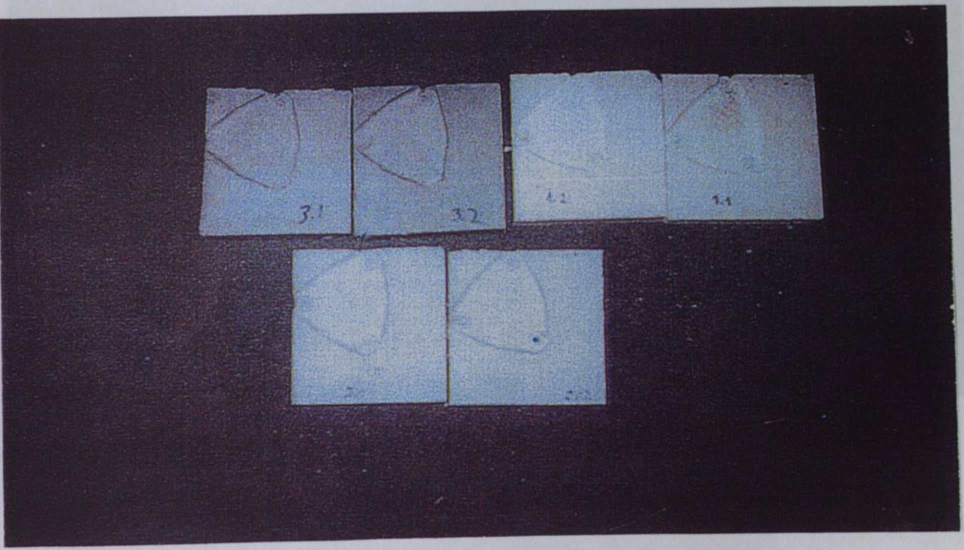


Figure 4.5. Molds 1,2 and 3 with the replications

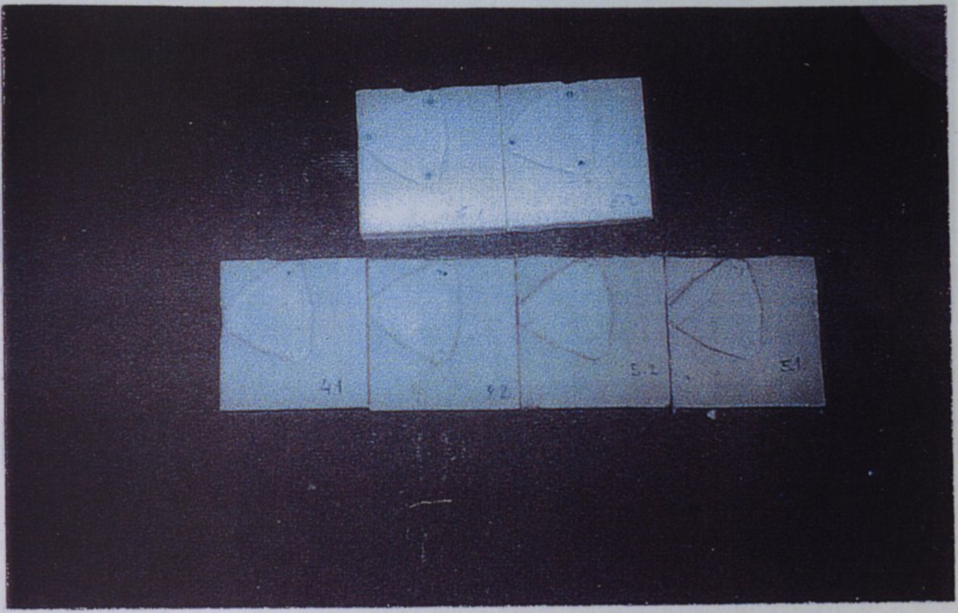


Figure 4.6. Molds 4,5 and 6 with the replications

Figure 4.7. Molds 7,8 and 9 with the replications

The surface roughness values of the molds are determined by using the device as shown in Figure 4.8.

Figure 4.8. Surface roughness measurement equipment

4.3. Mixture Optimization Experiments

4.3.1. Selecting the Design of Experiments

The aim of these experiments is to optimize the hardness value of cast part namely, front engine cover. To assure this optimization, different mixture compositions will be investigated. The selected statistical approach is extreme vertices design.

The goal of an extreme vertices design is to choose design points that adequately cover the design space. The Figure 4.9 shows the extreme vertices for two three-component designs with both upper and lower constraints.

The light gray lines in the Figure 4.9 represent the lower and upper bound constraints of the components. The dark gray area represents the design space, which experiments performed within. The points are placed at the extreme vertices of the design space.

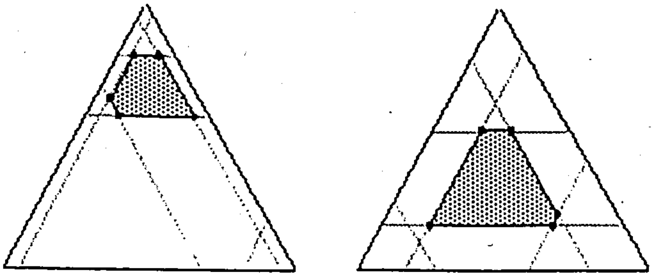


Figure 4.9. Extreme vertices design [28]

4.3.2. Extreme Vertices Design

Water composition by percentage is fixed to 40 per cent. Therefore, the remaining components have the total upper bound of 60 per cent, for composition settings.

Table 4.6. Design boundaries for the mixture components

Composition	*Boundries of Mixture Components*				*Mixture Design Properties*	
	Amount		*Ratio*		Components:	3
	Lower	*Upper*	*Lower*	*Upper*	Process Variables Selected:	0
A	0.32	0.6	0.533	1	Design Points:	9
B	0	0.18	0	0.3	Design Degree:	1
C	0	0.1	0	0.166	Mixture Total (In percentage):	60

4.3.3. Setting the Mixture Compositions

Plaster, fly ash, cement, talc and clay are chosen as the ingredients. Fly ash, cement and talc are defined as a single component namely, fct. With this assumption the total mixture experiment runs are handled with 3 main components which consist of plaster, fct and clay.

The L9 orthogonal array is the selected set of experiments to be performed. Run orders are randomized and design point types are shown in the Table 4.7.

Table 4.7. Selected design of experiment and component ratios

StdOrder	*RunOrder*	*PtType*	*Blocks*	*plaster*	*fly ash+cement+talc (fct)*	*clay*
5	1	0	1	0.46	0.09	0.05
8	2	-1	1	0.44	0.135	0.025
1	3	1	1	0.6	0	0
9	4	-1	1	0.39	0.135	0.075
3	5	1	1	0.42	0.18	0
7	6	-1	1	0.48	0.045	0.075
4	7	1	1	0.32	0.18	0.1
2	8	1	1	0.5	0	0.1
6	9	-1	1	0.53	0.045	0.025

Component recipes are given with Table 4.8 in weight basis. Every mixture has a total weight of 720 g.

Table 4.8. Recipes for the selected design of experiments

plaster(g)	*fly ash(g)*	*talc(g)*	*cement(g)*	*clay(g)*	*dry components (g)*	*water(g)*
552	60	30	18	60	720	480
528	90	45	27	30	720	480
720	0	0	0	0	720	480
468	90	45	27	90	720	480
504	120	60	36	0	720	480
576	30	15	9	90	720	480
384	120	60	36	120	720	480
600	0	0	0	120	720	480
636	30	15	9	30	720	480

4.3.4. Preparing the pattern and the flask for mixture experiment

Same pattern, which has also been used in Taguchi runs, is selected for the experiments. However, a rapid prototype pattern is assembled to the metal pattern. This new addition is needed for opening a gate in the mold, to be able to cast the aluminum. 21 (based on the foundry experience) thin channels are also opened on the lower halve of the mold to let the gas out of the mold easily. The runner pattern with modification is given with the following drawing.

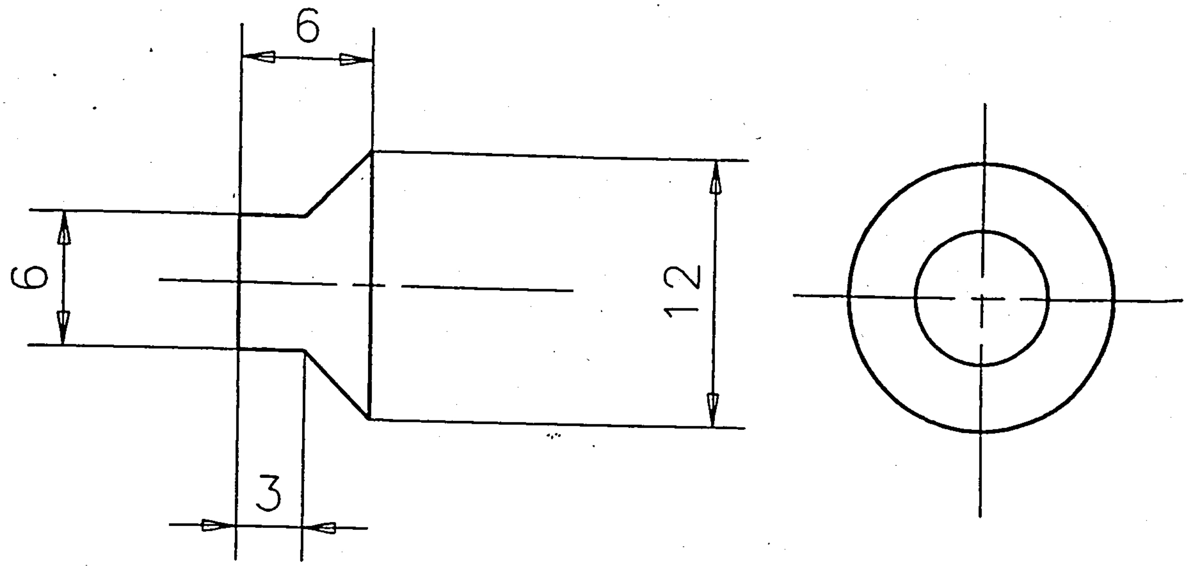


Figure 4.10. Casting pattern for the runner to the mold

A 200 x 200 x 50 mm. aluminum flask is used during the mixture experiments. This flask is bigger than the one used in Taguchi experiments to let the new pattern fit in the mold centrally.

4.3.5. Mixing of Slurry

A standard helical mixer with 100 mm. diameter and 1000 rpm is used for mixing process. Every run is mixed for one minute and poured into the flask immediately after 1 minute ends. A release agent for easy pattern removal is applied on the pattern and flask surfaces. Water temperature is fixed at 15 °C during the slurry preparations.

4.3.6. Removing the Molds From the Patterns

A predetermined 20 minutes is used as a standard setting time for all of the molds. After this time period, molds are carefully removed from the flasks and patterns. All of the molds stayed at room temperature for 24 hours and then put in the oven for drying. The cavities for the actual casting and the runner are seen for the three molds in Figure 4.11.

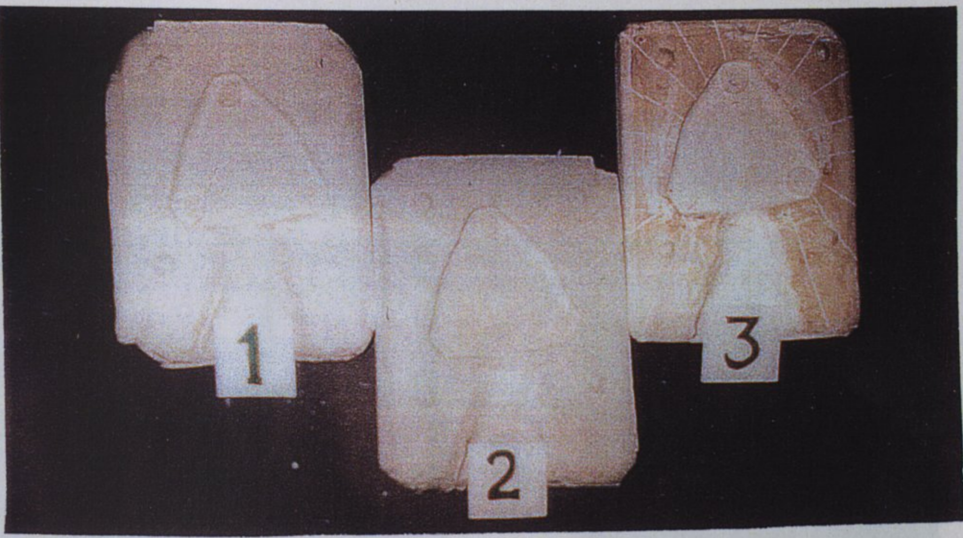


Figure 4.11. Casting molds No.1-3 prepared for the front engine cover

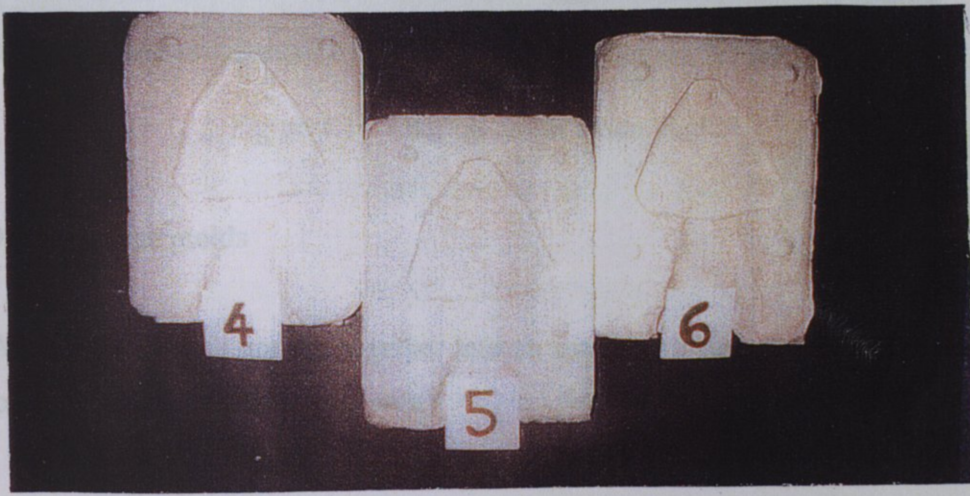


Figure 4.12. Casting molds No.4-6 for the front engine cover

Figure 4.13. Casting molds No.7-9 for the front engine cover

Selected molds are also shown as an assembly in Figure 4.14.

Figure 4.14. Casting molds assembled

4.3.7. Drying of the molds

All the nine molds are put together into an oven for 8 hours at 200 °C. Then, the dried molds are transferred to casting area.

4.3.8. Pouring Practice

Casting process is handled in Çorlu, Tekmetal investment casting facility. The 3xx series aluminum with given properties in Table 4.9. is used as the casting metal.

Table 4.9. Cast aluminum properties selected for the experimental study

3xx Series typical Aluminum Properties		
Yield Strength	165	MPa
Tensile Strength	248	MPa
Modulus of Elasticity	69	MPa
Brinell Hardness	80	
Density	2.705	g/cc
Melting Point	645	°C

Surface hardness values are measured in Brinell hardness (HB) with the device shown in Figure 4.15.

Figure 4.15. Surface hardness measuring equipment

5. RESULTS AND DISCUSSION

5.1. Taguchi Analysis on Set Time Response

First analysis of Taguchi experiment responses is based on set time measurements. Set time is something to be minimized to reduce the total process timing; the following formula (5.1) from the Taguchi methodology is used for the related analysis [23].

$$(S/N) = -10 \log_{10} 1/n(\Sigma y_i) \tag{5.1}$$

The delta value is a numerical index used for ranking the three factors. Delta value is calculated by subtracting the minimum value of the factor response (for instance temperature) from the maximum one. The biggest delta value shows the most significant factor on the response. As an example, the delta mean value of the temperature factor for the output set-time is shown below.

$$\text{delta (Temperature)} = 618.33 \text{ (max.)} - 362.5 \tag{5.2}$$

$$\text{delta (Temperature)} = 255.83 \tag{5.3}$$

Table 5.1. The response table for means (Output: Set-time)

Level	*Temperature (sec)*	*Mixing Time (sec)*	*Fly ash Additive (sec)*
1	618.33	760	525
2	589.16	449.16	595
3	362.5	360.83	450
Delta	255.83	399.16	145
Rank	2	1	3

Similarly delta ranking for standard deviations can be calculated. This ranking is shown in Table 5.2.

Table 5.2. The response table for standard deviations (Output: Set-time)

Level	*Temperature (sec)*	*Mixing Time (sec)*	*Fly ash Additive (sec)*
1	23.57	14.14	35.35
2	22.39	36.53	14.14
3	31.81	27.10	28.28
Delta	9.42	22.39	21.21
Rank	3	1	2

Finally the response table for (S/N) ratios, calculated with the Formula 5.1, is shown in Table 5.3. Signal to noise ratio results, in general, are the same with the ones obtained from the mean values analysis. This conclusion changes when the standard deviation is high compared to the mean values. However, the standard deviation is the major factor which effects the Taguchi analysis results.

Table 5.3. The response table for (S/N) ratios (Output : Set-time)

Level	*Temperature (sec)*	*Mixing Time (sec)*	*Fly ash Additive (sec)*
1	-55.18	-57.12	-53.12
2	-54.73	-52.74	-54.90
3	-51.09	-51.15	-52.98
Delta	4.08	5.97	1.92
Rank	2	1	3

With the ranking calculated, it can be concluded that mixing time is the most significant factor on the setting time output. In addition to this, it can be said that fly ash addition in the mixture does not have a major effect on the setting time.

The mean values vary between 350 and 750 seconds which show that the selected factors have a significant effect on the output variable set time. Graphical representation of experimental results can be drawn as in the following figures. Dotted line in the Figure 5.1 shows the general mean for the set of experiments.

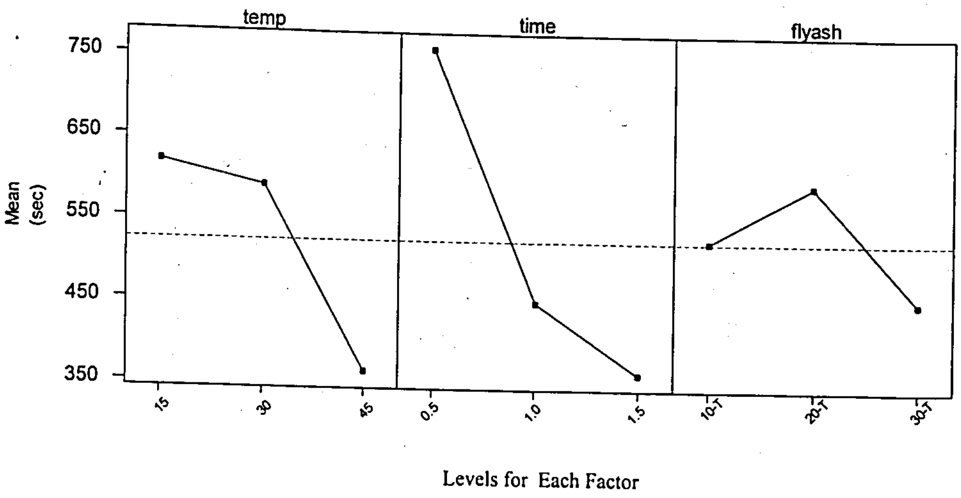


Figure 5.1. Main effect plot for means (Output: Set-time).

This main effect plot clearly figures that, with longer mixing time, mean value for the output (set-time) decreases. Temperature has a similar effect on setting time. With higher temperatures, mean for the set-time decreases.

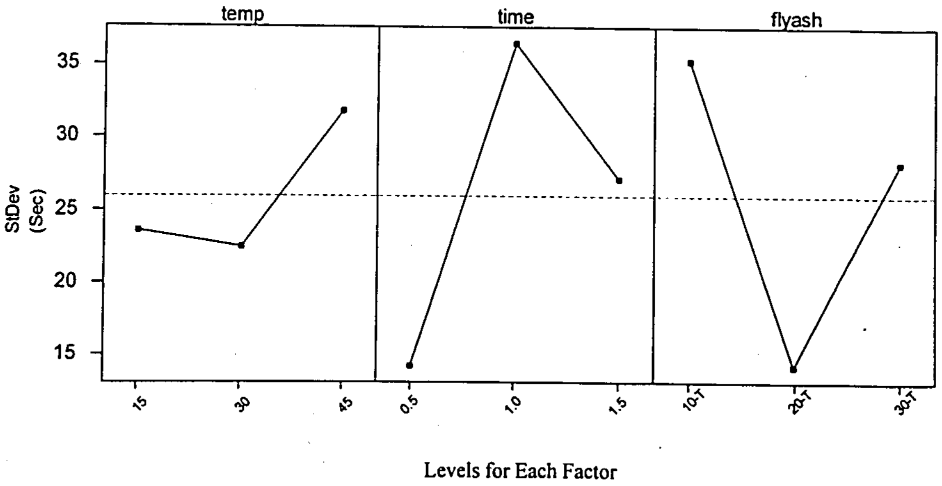


Figure 5.2. Main effect plot for standard deviations (Output Set-time)

(S/N) ratio in Taguchi analysis, mainly describes the sensitivity of the output chosen to each factor. Therefore it has been shown in figure 5.3. that mixing time is the most effective factor for the output.

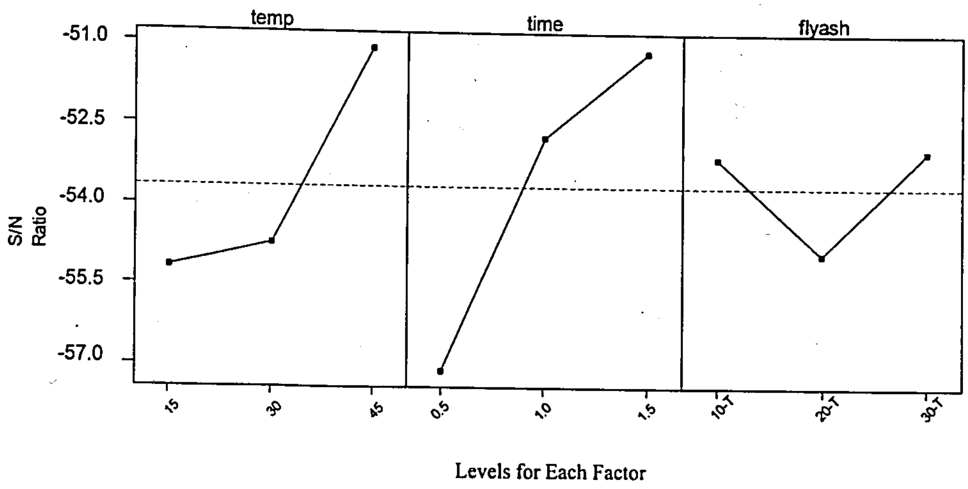


Figure 5.3. Main effect plot for (S/N) ratios (Output: Set-time)

5.2. Taguchi Analysis on Surface Roughness Response

The second response recorded in the experiments is surface roughness. Delta values are calculated with the surface roughness results obtained from the experiments. Procedure followed in set-time analysis is applied again.

To calculate the (S/N) ratio, the most important step in Taguchi methodology is to select the suitable formula. Most frequently used formulas were given with Table 3.5. Surface roughness, measured in R_a, is to be minimized, then the related formula for (S/N) ratio calculation, selected from Table 3.5, is the Formula (5.1).

Table 5.4 shows that surface roughness is mainly effected from mixing time. The best Ra value obtained from plaster mold casting is 0,75 *(μm)* [1].

Table 5.4. Response table for means (Output: Surface roughness in R_a)

Level	*Temperature (μm)*	*Mixing Time (μm)*	*Fly ash Additive (μm)*
1	2.42	2.51	2.48
2	2.27	2.27	2.34
3	2.46	2.37	2.32
Delta	0.19	0.24	0.16
Rank	2	1	3

In Table 5.5. it has been figured out that temperature has the highest effect on standard deviation for the surface roughness. Fly ash additive, also, has a significant effect on the standard deviation.

Table 5.5. Response table for standard deviations (Output: Surface roughness in R_a)

Level	*Temperature (μm)*	*Mixing Time (μm)*	*Fly ash Additive (μm)*
1	0.36	0.32	0.35
2	0.37	0.26	0.36
3	0.16	0.30	0.17
Delta	0.21	0.06	0.19
Rank	1	3	2

Table 5.6. shows the (S/N) ratio calculations for the second set of experiments. The ranking obtained from Taguchi (S/N) calculation is the same with the ranking shown in Table 5.4.

Table 5.6. Response Table for (S/N) Ratio (Output: Surface roughness in R_a)

Level	*Temperature (μm)*	*Mixing Time (μm)*	*Fly ash Additive (μm)*
1	-7.64	-8.00	-7.88
2	-7.18	-7.15	-7.39
3	-7.81	-7.49	-7.36
Delta	0.63	0.85	0.52
Rank	2	1	3

Graphical analysis is for the output surface roughness is given below;

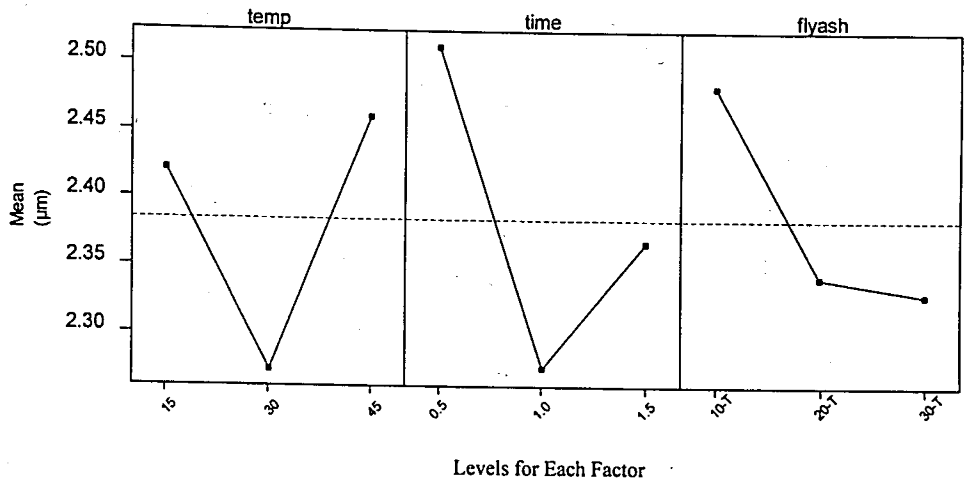


Figure 5.4. Main effect plot for means (Output: Surface roughness)

From Figure 5.4. it can also be said that fly ash additive has a positive effect on surface roughness minimization.

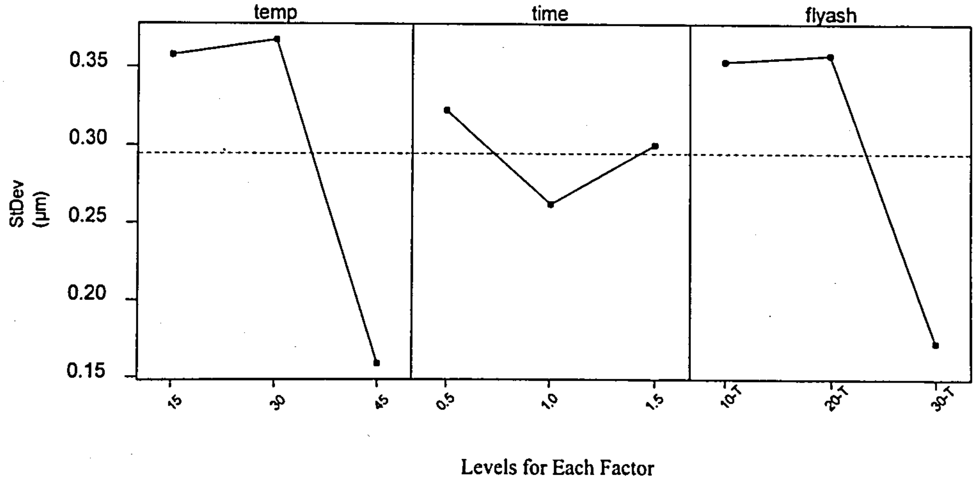


Figure 5.5. Main effect plot for standard deviations (Output: Surface roughness)

Fly ash and temperature factors can be used for decreasing the standard deviation.

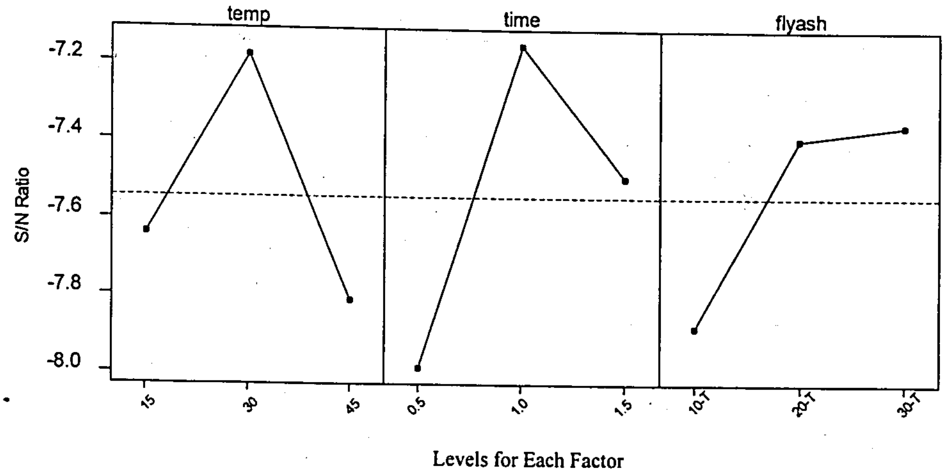


Figure 5.6. Main effect plot for (S/N) ratios (Output: Surface roughness)

As a summary for the Taguchi analysis performed on the second output surface roughness, the most significant factor is determined as mixing time. Additionally, the fly ash percentage increment in mixture has a positive effect on minimization the surface roughness.

5.3. Mixture Design Analysis

Hardness values are obtained for all nine castings. A linear model,

$$Y = b_1A + b_2B + b_3C \tag{5.4}$$

with three components (plaster, fly ash+cement+talc (namely;fct), clay) is obtained using the multilinear regression analysis. In multilinear regression analysis, following formulation is used [22].

$$y = X\beta + \varepsilon \tag{5.5}$$

the vector of least square estimators; β_{LE}, which minimizes

$$LE = y'y - 2\beta'X'y + \beta'X'X\beta \tag{5.6}$$

the least squares estimators must satisfy,

$$\frac{\partial LE}{\partial \beta} = 0 \tag{5.7}$$

which simplifies to,

$$X'X\beta_{LE} = X'y \tag{5.8}$$

then with the inverse of $X'X$ multiplication, the least squares estimator of β is (linear model coefficients);

$$\beta_{LE} = (X'X)^{-1}X'y \tag{5.9}$$

where y is the output matrix which is chosen as hardness values in this analysis;

$$\mathrm{y} = \begin{bmatrix} y_1 \\ y_2 \\ . \\ y_n \end{bmatrix} \tag{5.10}$$

and X is the matrix of the selected variables for the mixture analysis. These variables are plaster, fct, group and clay. The X matrix can be written as follows,

$$\mathrm{X}=\begin{bmatrix} 1 & (x_{11}-\overline{x_1}) & (x_{21}-\overline{x_2}) & . & (x_{k1}-\overline{x_k}) \\ 1 & (x_{12}-\overline{x_1}) & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ 1 & . & . & . & (x_{kn}-\overline{x_k}) \end{bmatrix} \tag{5:11}$$

Since only three variables are chosen as analysis factors, X matrix is calculated as follows (data used in analysis is shown in Table A.5.);

$$X=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & -0.02 & 0.045 & -0.025 \\ 1 & 0.14 & -0.09 & -0.05 \\ 1 & -0.07 & 0.045 & 0.025 \\ 1 & -0.04 & 0.09 & -0.05 \\ 1 & 0.02 & -0.045 & 0.025 \\ 1 & -0.14 & 0.09 & 0.05 \\ 1 & 0.04 & -0.09 & 0.05 \\ 1 & 0.07 & -0.045 & -0.025 \end{bmatrix} \tag{5.12}$$

where $\overline{x_1} = 0.46, \overline{x_2} = 0.09, \overline{x_3} = 0.05$. These values are the means for the factors plaster, fct and clay with the given order. Finally the output matrix y, measured in Brinell hardness, is written as;

$$y=\begin{bmatrix} 60.9 \\ 57.4 \\ 52.7 \\ 61.7 \\ 54.5 \\ 59.5 \\ 64.8 \\ 63.3 \\ 55.4 \end{bmatrix} \text{[HB]} \tag{5.13}$$

then if 5.11 and 5.12 equations are put into equation 5.8, estimated regression coefficients for hardness are;

$$\beta_{LE}=\begin{bmatrix} 88.019 \\ 100.019 \\ 188.419 \end{bmatrix} \tag{5.14}$$

Table 5.7 summarizes the regression analysis results.

Table 5.7. Regression coefficients

Term	*Coefficients*
Plaster	88.019
Fly ash+cement+talc (fct)	100.019
Clay	188.419

With these coefficients; the linear model can be written as:

$$y\ (\text{hardness}) = 88.019(\text{plaster}\ \%) + 100.019(\text{fct}\ \%) + 188.419\ (\text{clay}\ \%) \qquad (5.15)$$

Following R- sq value shows that how much of the data fits with the model:

$$\text{R-Sq} = 95.07\% \qquad (5.16)$$

A cox (proportion) trace output can be drawn according to fitted linear model:

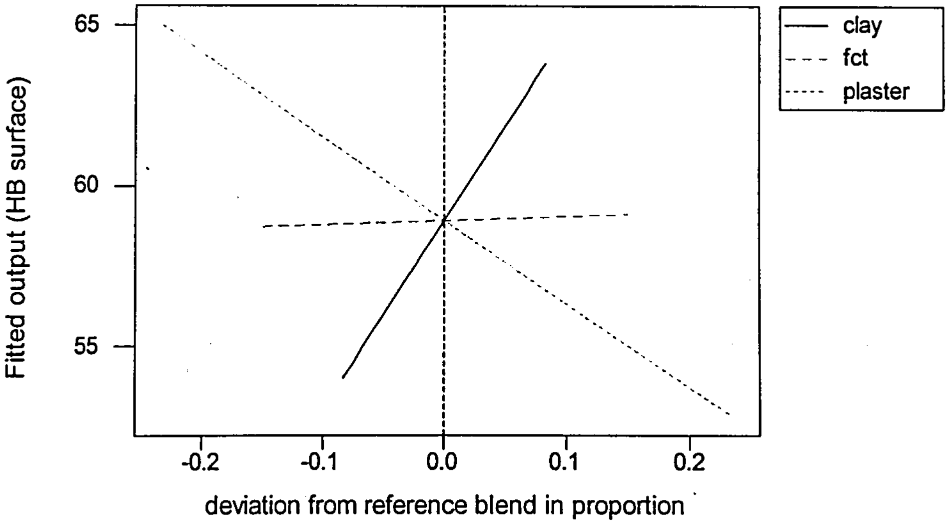


Figure 5.7. Cox trace output, the variation in HB surface with respect to blend composition

Figure 5.7 is showing that the deviation of clay proportion on positive direction, results with an increment on HB surface where plaster has an adverse effect.

A 3-D plot is also figured out to visualize the model obtained from the regression analysis.

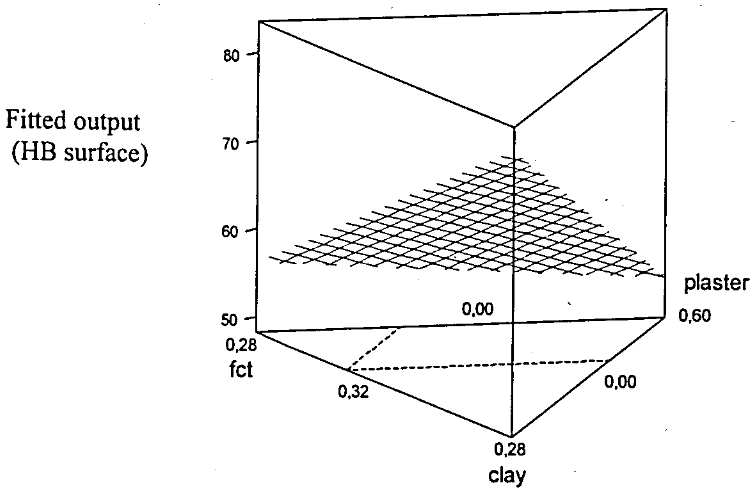


Figure 5.8. The mixture surface plot

The mixture surface plot clearly shows that the percentage of clay in the mixture, mainly affects the hardness value. Increment in clay proportion results with higher hardness values. This effect is figured out with a contour graph which shows the fitted model lines for the given hardness values.

From Figure 5.9. it is possible to determine the relative amounts of plaster, fct and clay in a mixture for a desired HB value.

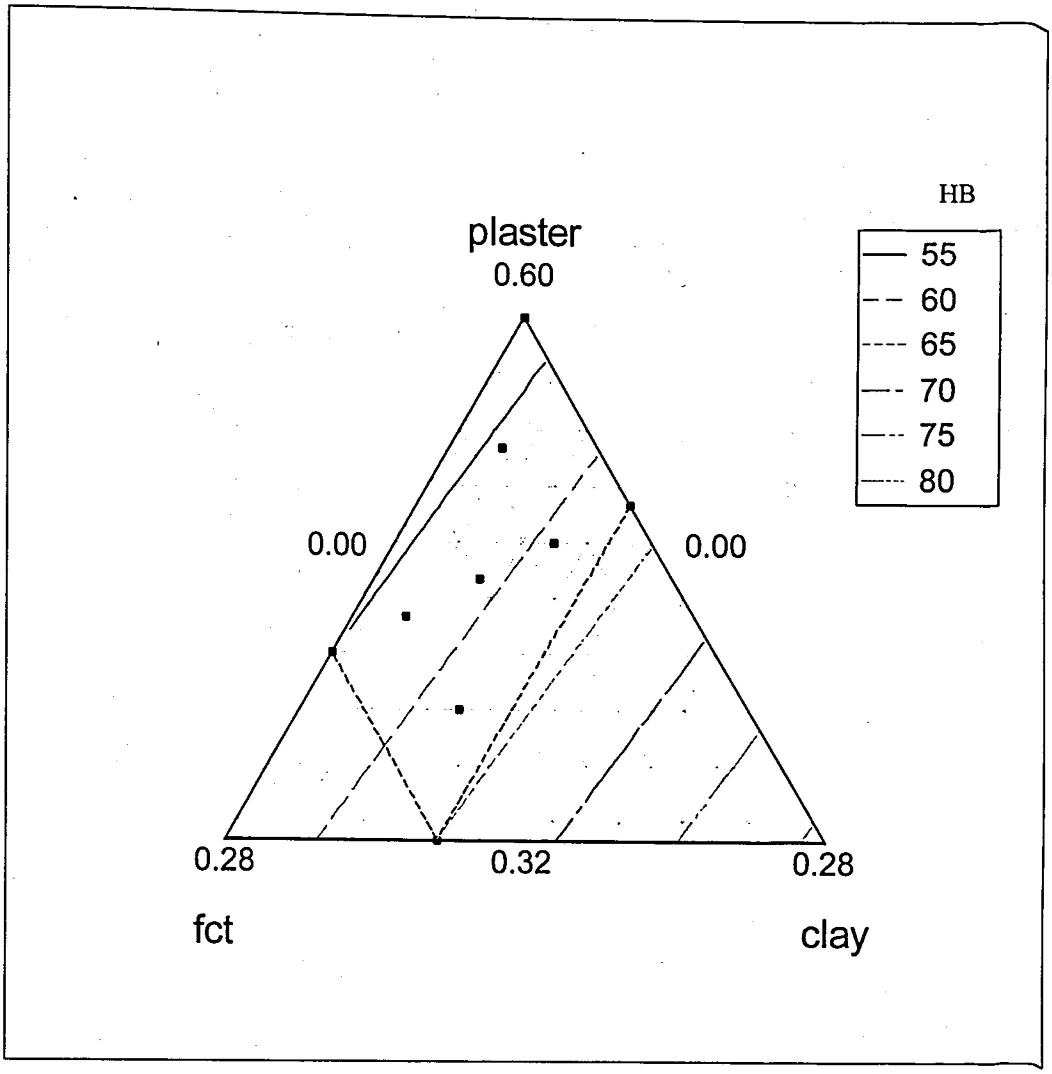


Figure 5.9. Contour plot for hardness values

6. CONCLUSIONS AND RECOMMENDATIONS

Plaster mold casting has chosen as the precision casting method. Statistical techniques, Taguchi methodology and mixture designs have been used for analyzing the compositions and parameters. Different compositions of mixture and process parameters have been studied Experimental results reveal that the set-time of the plaster mold decreases when the mixing time and temperature, in the process increase. This is an expected conclusion since with longer mixing, plaster particles disperse better in the slurry. It has also been concluded that fly ash addition stabilizes the plaster mold casting process.

With fly ash addition, surface quality of the molds is improved. The fine fly ash particle size results a better binding property on the mold surfaces with minimum surface roughness. These suggest that fly ash can be utilized as an additive in plaster mold compositions.

Hardness value of the castings, increases by the addition of clay into mixture compositions. The increase in the hardness of the material can be explained by the increase of the cooling rate of the mold. Faster cooling makes the casting more brittle. A sample linear model has been derived to obtain desired hardness values by changing the mold ingredient compositions. The total process timing is given as follows;

Table 6.1. The total process timing in the present work

Process Steps		***Duration***
Preparation of Pattern and Flasks		
	Cad model for Rapid Prototyping	1 week
	Rapid Prototyping	0.5 week
Mold Preparation		0.5 week
Drying of the molds		0.5 week
Casting		0.5 week
	Total time needed for the prototype development	3 weeks

In general, the conventional prototyping and sample manufacturing takes between three to six months. Therefore, the roadmap followed in this study can be used as a prototyping process or a preliminary investigation before a precision casting process to obtain some design and functional modifications [27,28]

APPENDIX A: EXPERIMENTAL DATA

All of the test results obtained from the experiments are summarized. This appendix includes the test data for both Taguchi and mixture design experiments.

Table A.1. The test data used in Taguchi analysis for output set-time

temp (C)	*time(min)*	*fly ash(type)*	*set time1(sec)*	*set time2(sec)*
15	0.5	10	960	945
15	1	20	540	510
15	1.5	30	350	405
30	0.5	20	885	900
30	1	30	520	555
30	1.5	10	360	315
45	0.5	30	450	420
45	1	10	240	330
45	1.5	20	375	360

Table A.2. The test data used in Taguchi analysis for output surface roughness

temp (C)	*time (min)*	*fly ash (fct)*	*Ra1 (μ m)*	*Ra2 (μ m)*
15	0.5	10	2.54	3.27
15	1	20	2.32	1.71
15	1.5	30	2.42	2.24
30	0.5	20	2.58	2.09
30	1	30	2.56	2.16
30	1.5	10	2.44	1.77
45	0.5	30	2.36	2.21
45	1	10	2.38	2.48
45	1.5	20	2.44	2.87

Table A.3. The surface roughness test data used in Taguchi analysis

Spcm	***Ra1 (μ m)***	***Ra2 (μ m)***	***Ra3 (μ m)***	***Ra4 (μ m)***	***Ra5 (μ m)***	***Ra6 (μ m)***	***Avrg (μ m)***
11	2.55	2.12	3.23	2.15	3.04	2.16	2.54
12	3.2	3.65	3.46	3.27	3.03	3.03	3.27
21	2.26	2.45	2.1	2.26	2.48	2.42	2.32
22	2.14	1.57	1.61	1.74	1.58	1.67	1.71
31	2.21	2.4	3.08	2.26	2.12	2.46	2.42
32	2.3	2.18	2.53	2.48	2.13	1.85	2.24
41	2.27	2.27	2.63	3.03	2.61	2.7	2.58
42	1.86	2.11	2.01	2.23	2.02	2.36	2.09
51	2.89	2.67	2.14	2.24	3.08	2.38	2.56
52	1.77	2.01	2.38	2.33	2.1	2.4	2.16
61	2.07	2.55	2.52	2.64	2.26	2.63	2.44
62	1.94	2.05	1.7	1.78	1.65	1.52	1.77
71	2.32	2.71	2.4	2.25	2.12	2.38	2.36
72	2.15	2.02	2.16	2.03	2.28	2.64	2.21
81	2.33	3.16	2.33	1.94	2.1	2.44	2.38
82	2.53	3	2.37	2.2	2.28	2.51	2.48
91	2.71	2.73	2.72	2.37	2.21	1.95	2.44
92	3.11	2.75	2.42	3.08	3.45	2.42	2.87

Table A.4. Hardness test data used in mixture analysis

Specimen	***Meas.1***	***Meas.2***	***Meas.3***	***Meas.4***	***Meas.5***	***Average (Brinell)***
1	60	63	62	61.5	58	60.9
2	55	59	60	56	57	57.4
3	52	53	51.5	53	54	52.7
4	62	60.5	59	64	63	61.7
5	57	53	54.5	53	55	54.5
6	57	62.5	62	59	57	59.5
7	64.5	62.5	64	66	67	64.8
8	60	66	62	64	64.5	63.3
9	54	55.5	58	55	54.5	55.4

Table A.5. The test data for mixture analysis

StdOrder	*RunOrder*	*PtType*	*plaster*	*fct*	*clay*	*Hardness (Brinell)*
5	1	0	0.46	0.09	0.05	60.9
8	2	-1	0.44	0.135	0.025	57.4
1	3	1	0.6	0	0	52.7
9	4	-1	0.39	0.135	0.075	61.7
3	5	1	0.42	0.18	0	54.5
7	6	-1	0.48	0.045	0.075	59.5
4	7	1	0.32	0.18	0.1	64.8
2	8	1	0.5	0	0.1	63.3
6	9	-1	0.53	0.045	0.025	55.4

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