Parametric Analysis of Cold Chamber High Pressure Die Casting of LM9 and ADC12 Aluminium Alloys

A dissertation submitted in partial fulfilment of requirement for the award of degree of

Master of Engineering

in

Production Engineering

Submitted by

KRISHNA MURARI KATARA

Roll No.: 801585015

Under the guidance of

Dr. VINOD KUMAR SINGLA

Associate Professor

DEPARTMENT OF MECHANICAL ENGINEERING

THAPAR UNIVERSITY

PATIALA (PB), INDIA, 147004

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Certificate

I hereby declare that the work done in this thesis entitled "**Parametric Analysis of Cold Chamber High Pressure Die Casting of LM9 and ADC12 Aluminium Alloys**" submitted towards partial fulfillment of requirement for award of degree of **Master of Engineering** in **Production Engineering, Thapar University, Patiala,** is an authentic record of the work carried out by me under the supervision and guidance of **Dr. Vinod Kumar Singla, Associate Professor, Mechanical Engineering Department, Thapar University, Patiala.**

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

Dated: 17/07/2017

Krishna Murari Katara

Registration No.: 801585015

This is to certify that above declaration made by the student concerned is correct to the best of our knowledge and belief.

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Dr. Vinod Kumar Singla

Associate Professor

Mechanical Engineering Department

Thapar University, Patiala

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Krishna Murari Katara

Registration No.: 801585015

ME (Production Engineering)

Abstract

High pressure die casting (HPDC) is a favorable manufacturing process for casting of aluminium and magnesium alloys components like gear-box, piston, cylinder, transmission cover, laptop housing etc. HPDC used in the current study is applied for casting the thin walls as well as components of intricate shapes. The final machining and finishing operation on components produced using HPDC are negligible. Higher production volume, higher dimensional accuracy and better surface finish with required tolerances can be achieved by using high pressure die casting. Experimental investigation and property analysis is carried out in the present work. Response surface methodology has been used to develop the input output relations. Pouring temperature of molten metal, injection pressure, die holding time and die coating have been considered as input parameters while density, hardness and surface roughness have been considered as output parameters. LM9 and ADC12 aluminium alloys have been used as raw materials. Experimental work has been carried out on cold chamber high pressure die casting machine. Based on experiments carried out, Box-Behnken design technique has been used to develop nonlinear models. Surface morphology has been also studied using scanning electron microscopy.

Keywords: HPDC; Response surface methodology; Box-behnken design; LM9 alloy; ADC12 alloy, Injection pressure.

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Chapter 1

Introduction

1.1 Introduction

High pressure die casting (HPDC) is a vital process for producing intricate shapes, reducing the casting defects, improving the quality of cast products and reducing the lead time. It is mainly used for high production volume, better surface finish and higher dimensional accuracy [1].

In this process molten metal is poured into shot sleeve and forced into die cavity and allow solidifying under die pressure to cast the products. HPDC is preferred for aluminium and magnesium alloy components, which is widely used for automotive and other industrial applications.

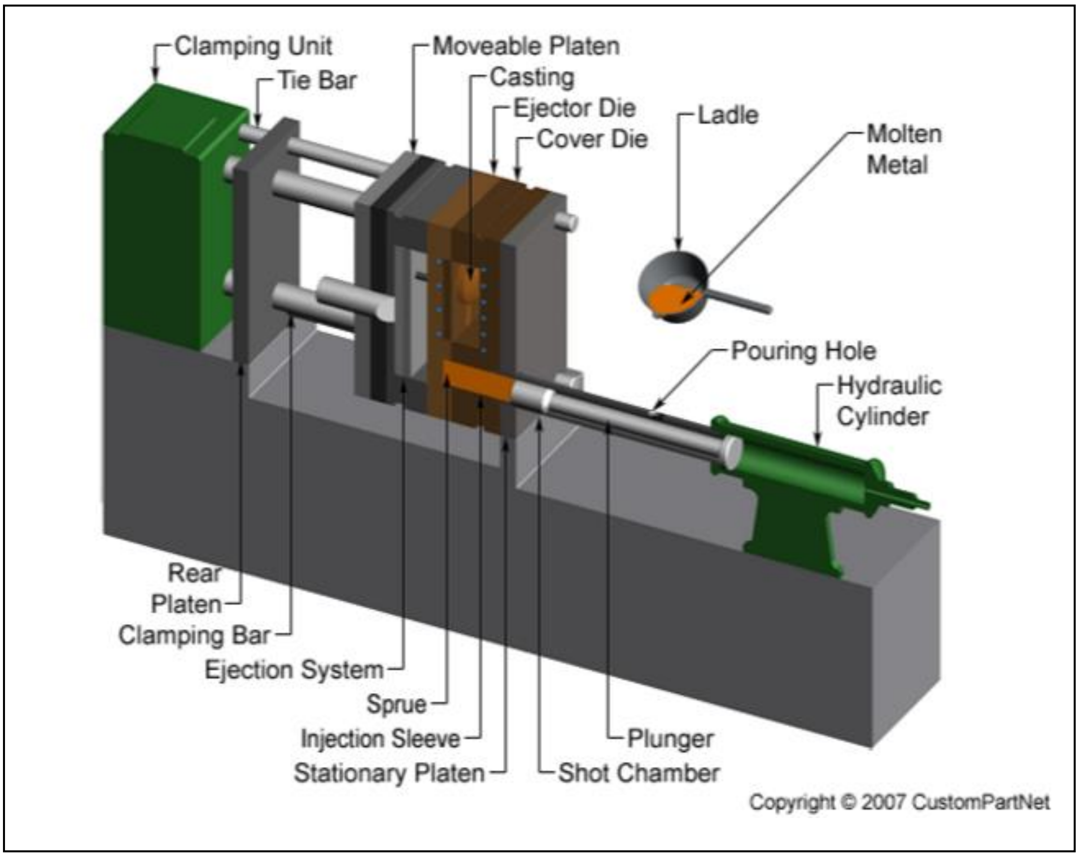

Figure 1.1: High Pressure Die Casting Machine (Cold Chamber Die Casting)

The products cast from the HPDC are gear box transmission, steering wheel, clutch plate, laptop housing etc. The temperature of molten metal is around 700^0C. Magnesium alloys are widely used for industrial application due to its lighter weight, environment friendly, low cost and highest strength to weight ratio [2], while aluminium alloys are widely used for industries due to light weight, excellent castability, good weldability, good thermal conductivity, excellent corrosion resistance, and good wear resistance properties [3].

1.2 History

Die casting was developed during 19^{th} century. According to collected data, the first manually operated casting machine for casting printing type was patented by Sturges in 1849. In 1892, components were produced for phonographs and cash registers by using die casting machine. When H.H Franklin Company started die casting of babitt alloy bearing for automobile, mass production of products further increased. The first die casting alloys were lead and tin. After the development of zinc alloy just preliminary to World War 1, uses and importance of lead and tin alloys decreases. Magnesium and copper alloys were developed after the development of zinc alloy. During the 1930’s, large no of alloys were developed which are available today in the market. According to 2015 data, there were approximately 375 die casters available in North America. Aluminium, copper, magnesium and zinc alloys mainly used for production of die cast products [4-5].

1.3 Advantages of Die Casting Process [5]

Die casting is an efficient, economical and most versatile casting process used for casting variety of parts compare to other manufacturing processes. Parts cast from die casting process have long service life. The other advantages of die casting process are:

1. Dimensional accuracy of die cast parts are excellent
2. Die casting parts require less or no machining
3. It provides higher production rate
4. Die casting process is capable of producing intricate shapes and thin wall parts with better surface finish
5. Die casting parts have light weight and better performance
6. Die casting parts have excellent corrosion resistance, and good wear resistance properties

1.4 Die Casting Process

Die casting is a manufacturing process which is used for casting of complex parts with the help of reusable metal dies. It is mainly used for mass production of parts. In die casting process metal is firstly melted in a crucible furnace which is made of SiC.

The die used in HPDC consists of two parts: one is fixed half and another one is movable half or ejector half. After completion of casting, when die is opened the casting remains in the moving half, this is ejected by using the ejector pins manually or automatically and after solidification of molten metal finished products is taken out from die cavities with the help ejector pins [6]. Die casting machine ranges from 80 tons to 4000 tons. There are two types of die casting processes:

1. Hot chamber die casting process
2. Cold chamber die casting process

1.4.1 Hot Chamber Die Casting Process

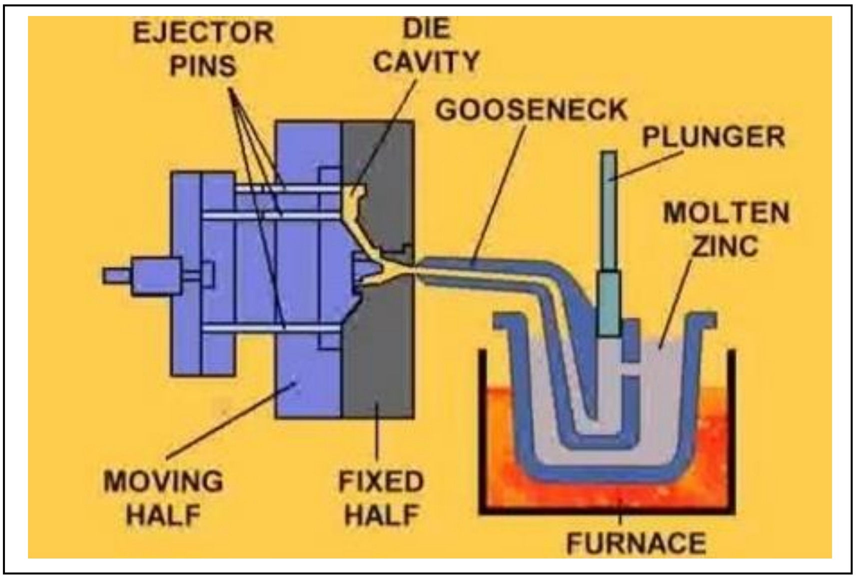

Figure 1.2: Hot chamber die casting machine [8]

Hot chamber die casting machine is used for zinc, nickel, lead and low melting point alloys [7]. In hot chamber die casting furnace is an integral part of machine. It is attached to the machine by metal feed system called gooseneck.

It is mainly used for casting which is small in size (.03kg to 40kg). The pressure range varies from 7 Mpa to 35 Mpa. In this casting process there is less chance to entrapment of air in molten metal due to minimum contact between air and metal to be injected [5].

Hot Chamber Die Casting Process Cycle:

1. Firstly die is closed and plunger is at his top position, inlet port is open and molten metal is entering into the cylinder.
2. Plunger moves downwards and pushes molten metal into die cavity through gooseneck and nozzle.
3. When molten metal solidify plunger moves upwards and dies open.
4. Now casting remains in the moving half.
5. Ejector pins are used to eject the casting from die cavity.

1.4.2 Cold Chamber Die Casting Process

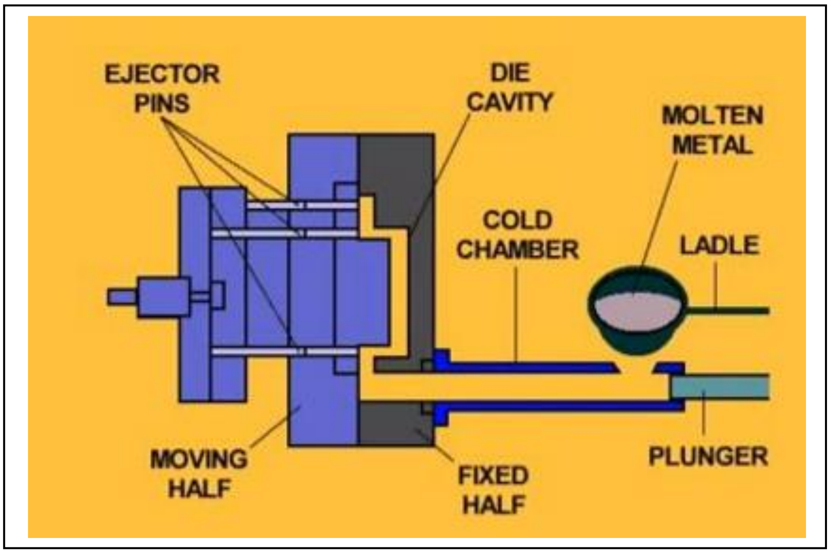

Figure 1.3: Cold chamber die casting machine [8]

Cold chamber high pressure die casting machine is used for high pressure and higher melting point alloys such as aluminium, magnesium and copper based alloys. These alloys cannot be used in hot chamber die casting because it will damage the pumping system of the machine. In cold chamber high pressure die casting metal melting furnace is separate from the machine.

Pressure range varies in cold chamber high pressure die casting process from 25Mpa to 300Mpa. It is used for large size castings. In this casting process molten metal is forced into die cavity at high speed due to which air can entrapped into molten metal, which can cause gas porosity in castings. It can produce quality part to near net- shape parts, due to high injection pressure. Cycle time for casting a part varies from 10 sec to 2 min [9].

Dies used in cold chamber die casting is made up of hardened steel. The strong and hard metals such as steel and iron cannot be die cast [10]. These metals are melted around 700^{o}C (aluminium alloy) in a furnace.

Cold Chamber Die Casting Process Cycle:

1. Firstly die is closed and molten metal is poured into shot sleeve by ladle either manual or automatic.
2. Plunger forced molten metal into die cavity at high pressure.
3. Molten metal solidify inside die cavity after that plunger is withdrawn from cavity.
4. Now die is open and casting remains in the moving half.
5. Ejector pins are used to eject the casting from die cavity.

1.5 Die Construction

Dies plays an important role for casting of parts. It is mainly consist of two parts ejector die and cover die. Dies are made up of alloy tool steels like H 13 tool steel. Ejector pins are located on ejector die or movable die halves, which are used for easy removal of die cast parts and allow for cooling and lubricant. Gating and runner system are attached to the cover die or fixed die.

Molten metal enters into die cavity through sprue hole in cover die. When both ejector die and cover die are in close contact, hydraulic pressure is exerted by machine for tight contact between dies [5].

Basic functions of dies are:

1. To hold the molten metal into die cavity
2. To extracted heat from molten metal for solidification of casting
3. To remove the casting from die cavity

1.6 Types of Die Cavity

There are two types of die cavities:

1. Single cavity die
2. Multiple cavity die

1.6.1 Single Cavity Die

Single cavity die produces only one part at a time. This type of cavity is used for less production volume or production of complex shapes parts.

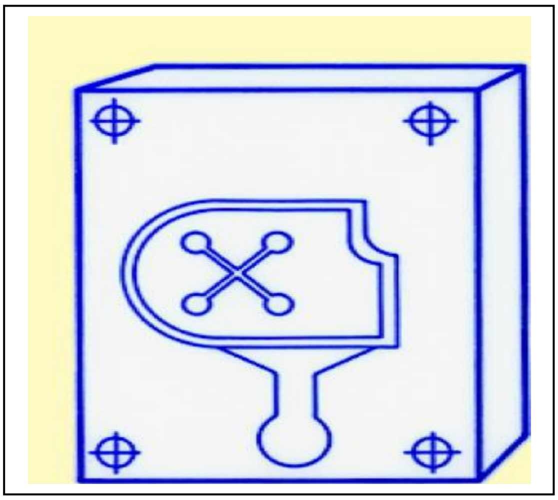

Figure 1.4: Single-cavity die [5]

1.6.2 Multiple Cavity Die

Multiple cavity die consist of more than one die cavity and all die cavity are identical. It is mainly used for higher production volume.

Figure 1.5: Multiple cavity die (clutch plate) at Thapar University

1.7 Coating [11]

Coating plays an important role in the field of die casting. It is used for easy removal of casting from the die surfaces. The main purpose to coat the die surfaces are given below:

1. To improve the quality of parts
2. For easy removal of casting
3. To increase the die life
4. To reduce finishing cost

In HPDC process, two types of mold releasing agents are used for easy removal of parts from die and avoid the direct contact of die surface with the parts. One mold releasing agents are water soluble releasing agents and another one are water insoluble mold releasing agents. Among these mold releasing agents, water insoluble mold releasing agents are not widely used because of high smoke and flammability. Water soluble releasing agents such as silicon oil, natural wax, mineral oil are widely used for surface active agent or greatest possible providing agent, are annexed [12].

Chapter 2

Literature survey

2.1 Introduction

The objective of literature survey is as follows:

1. To determine the effect of various process parameters such as pouring temperature of molten metal, injection pressure, die holding time and types of coating on mechanical properties of parts produced by cold chamber high pressure die casting.
2. To minimize the defects in cold chamber high pressure die casting.
3. To investigate the relationship between microstructure and thermal condition of casting.

This literature survey has been divided into following section:

a) Effect of pouring temperature of molten metal
b) Effect of injection pressure
c) Effect of cooling
d) Effect of porosity
e) Effect of addition of material
f) Effect of coating and die lubricants

Dargusch et al. [13] used in-cavity pressure sensors to determine the effect of process parameter on the quality of high pressure die casting machine. It was found that the porosity of the part was decreases when the injection pressure was increases, and when the casting velocity was increases, porosity was increases. Delay time has no effect on porosity. They investigated the rapid solidification in particular sections of the castings resulting in shrink or gas porosity.

Maleki et al. [14] studied the effect of process parameter on the microstructure of LM 13 aluminium alloy manufactured from squeeze casting. It used the pressure and die temperature as input parameter. It was investigated that due to the application of pressure grain size decreased during solidification.

Abtan and Ghlaim et al. [15] studied the effect of pressure on porosities. They used the squeeze casting process and pressure die casting process. Various tests were performed to show the improvement in properties by using both processes. It investigated that hardness and density in pressure die casting were lower than the squeeze casting.

Verran et al. [16] used design of experiment technique to analyses the effect of injection parameters on density of work material. It was used fast shot velocity, slow shot velocity, and upset pressure as input parameters. It was found that fast shot velocity and upset pressure are the main factors which affect the density of work material while slow shot velocity has the negligible effect on density.

Wang et al. [17] investigated the applications of PVD coatings to improve the die life. It investigated the effect of coating on heat checking resistance, heat checking resistance reduced due to the coating only H19 steel. It also concluded from the experiment if both corrosion/erosion resistance and heat checking resistance is required if PVD coated HWM steels should be used. Only heat checking resistance is required if H19 steel inserts should be used. Only erosion/corrosion resistance and impact toughness is required if Marlok steels or PVD coated H13 steel should be used.

Mitterer et al. [18] investigated the parameters which affected the die surfaces. Parameters were erosion, corrosion, soldering, heat checking, gross cracking and oxidation. They found die steel erosion, soldering of aluminium reduced using hard coatings based on carbides or nitrides of transition metals and improvement in thermal cracking resistance was also found. The best combination was found using hard coatings based on carbides or nitrides of transition metals TiN and Ti(C, N).

Salas et al. [19] studied to improve the tribological performance of die casting dies for aluminium alloys by coating on H13 steel substrates. The main purpose of this studied to increase the die life and die surface performance and also designed the multilayer coating system. The coatings investigated were CrN, CrC, ZrN, MoZrN, TiAlN, TiN/TiC, NiAl, NiAlN etc out of which only some of them have excellent wear and adhesion performance.

Hajjari et al. [20] studied about the shrinkage porosities produced in2024 aluminium alloy. It was investigated that large no. of shrinkage porosities was produced in microstructure of 2024 aluminium alloy because of its long solidification range. Microstructure and tensile properties were studied by varying the squeeze pressure. They found that microstructure will be finer and ultimate tensile strength will be increase by increasing the squeeze pressure.

Obiekea et al. [21] studied microstructure analysis of die cast samples A1350 alloy. They analysed change in structural morphology of grain size under different pressure. Tensile strength, hardness and impact strength were also affected by applied pressure. It was found that hardness was increased from 77 to 86 HRN and impact strength increased from 3.98 to 4.44 joules. They also found that finer grain size under the pressure of 1400 kg/cm^2.

Zhang et al. [22] Used aluminium oxide particles to improve the microstructure and mechanical properties like tensile strength and yield strength of LM 24 aluminium alloy. It was found that with the addition of in situ aluminium oxide particles, the coarse primary Si phase was vanished from the sight. It was found that with the addition of 0.1%Sb in LM24 aluminium alloy, the mechanical properties like tensile strength and yield strength was increased by 16 MPa and 52 MPa as compare to LM24 aluminium alloy.

Hu et al. [23] Used commercial software (MAGMA) to simulated filling time, temperature distribution, filling trace during the die casting process. It was used scanning electron microscope (SEM), and optical microscope to determine the phase distribution and surface microstructure of AZ91D magnesium component, which is casted on hot chamber die casting machine. On the outer skin of the die-cast components decrease in corrosion resistance along the filling trace has been observed.

Syrcos et al. [24] analyzed the die casting process parameter like hydraulic pressure, filling time, piston velocity, melting temperature of AlSi9Cu13 aluminium alloy. Taguchi's method was used to analyze the influence of process parameter on casting density. It was found that these die casting process parameters adversely affect the casting density of AlSi9Cu13 aluminium alloy.

Penghuai Fu et al. [25] investigated the effect of process parameters of AM50 magnesium alloy on the mechanical properties of low pressure die casting. The process parameters were die temperature casting temperature, holding pressure, filling time. It was found that as increasing filling time and casting temperature grain structure become coarse, resulting lower mechanical properties and density were obtained. It was also found that casting density and mechanical properties with fine grain microstructure were improved due to increasing pressure holding time. It was also found that mechanical properties were reduced and grain microstructure become coarse due to increase in casting pressure. Optimal mechanical properties and fine grain microstructure can be obtained, when combination of both die temperature and holding pressure high.

Kumar et al. [26] optimized the process parameter such as pouring temperature of molten metal, types of coating and cooling, injection pressure of molten metal, on the mechanical properties of HPDC by using LM6 aluminium alloy. Injection pressure was the major factor that affects the mechanical properties. It was found that due to the use of oil cooling as compared to air and water cooling and increasing pouring temperature of molten metal, hardness of die cast component improved significantly. It was also found that with increasing injection pressure porosity in casting decrease.

Hu et al. [27] studied the effect of injection pressure, fast shot velocity, Speed Transition Point Locations and Aging effect on mechanical properties like density, tensile strength, yield strength, elongation. It was found that along the die filling direction density of a work piece decrease and tensile strength, yield strength, increased by 29.4 MPa, 46.2 MPa, respectively and elongation decreased from 13.77 to 5.5% but after 1 hour aging it increase upto 11.48.

Kittur et al. [28] used response surface methodology to developed input output relation. The input parameters were injection pressure, die holding time, fast shot velocity and phase change over point, surface roughness, and hardness were output parameters. It was used box-behnken design and central composite design for this work. It was found that for response hardness and surface roughness, the performance of CCD is good as compare to BBD while for response porosity the performance of BBD is good as compare to CCD. The value of surface roughness, porosity in CCD was decreased by 8.28, 59 respectively while hardness value increased by 1.75 as compare to BBD.

Prabhu et al. [29] studied the effect of process parameters on defects in high pressure die casting. Various process parameters were pouring temperature, cooling medium, tool temperature, and pouring time, various types of defects are blow hole, bubble and flash defects. Design of experiment by taguchi method used to conduct the experiment. Blowhole defect was significantly affected by pouring temperature, and bubble defects was significantly affected pouring time, and flash defect was significantly affected by tool temperature and cooling medium.

El-Mahallawy et al. [30] investigated the effect of process parameter(velocity and pressure) on thermal conditions and on mechanical properties of magnesium alloy. Change in pressure or velocity has no effect on temperature distribution. It was found that increased in velocity or pressure bulk density of casting was increased also tensile strength increased. It was also found that velocity and pressure has no effect on surface hardness and ductility.

GUO et al. [31] analyzed the effect of input parameter, thickness of casting and alloy on interfacial heat transfer coefficient. It was used ADC12 and AM50 alloy for this work. It was found that input parameters affect only the IHTC peak values. For thinner steps fast shot velocity and for thicker steps initial dies surface temperature were the major factor which affect the IHTC peak values. If fast shot velocity would be higher than IHTC peak values would be higher and if initial die surface temperature higher, lower the IHTC peak values. It was also found that when casting alloy was ADC12, then there was a closed contact between work piece and die during solidification process. It was also concluded that flow velocity and pressure transfer behavior inside work piece changed due to the change in step thickness, which result in different steps different IHTC profile obtained.

Li et al. [32] Used vacuum-assist high-pressure die casting to enhance the mechanical properties of AZ91D alloy. It was found that by employing a flow distributor during vacuum assist die casting process, tensile strength increased 20%, double elongation, treble low fatigue cycle life were obtained. Due to the use of vacuum in die casting would reduce the gas porosity, due to which mechanical properties were enhance. It was also found that with the use of flow distributor and vacuum porosity was decrease by 90% and 80% ESC was obtained as compare to conventional die casting.

Lee et al. [33] investigated the effect of process parameters (injection pressure, gate velocity, melting temperature) on micro porosity of AM50 magnesium alloy. Novel digital image analysis technique was used to determine the amount of gas porosity, shrinkage porosity, pore size distribution, and total porosity. It was concluded that gas porosity significantly reduce due to the application of injection pressure. It was also conclude that gas porosity can also be significantly reduce due to the reduction of gate velocity and melting temperature. It was also conclude that shrinkage porosity and pore size distribution also reduced due to the reduction of gate velocity.

Zhao et al. [34] discussed about the gas entrapment defects of ADC12 aluminium alloy plate during the cavity filling of die casting process. It was analyzed the effect of fraction and size on mechanical properties. It was found that with the same amount of gas entrapment, smaller porosity and more even distributed size would be benefit to mechanical properties. It was also found that maximum size and porosity fraction should not be more than 169 μm and 3.3% respectively.

Farahany et al. [35] used situ thermal analysis technique to found out the characteristic parameters of eutectic phase in ADC12 aluminium alloy with the addition of Bi, Sb, Sr, under different cooling rate. It was conclude that additives affects more Al-Si phase as compared to Al-Cu phase. It was found that with the addition of Sb, Bi recalescence increase with increased cooling rate but with the addition of strontium recalescence decreased. It was also conclude that with the addition of antimony and strontium the temperature of Al_2Cu particles increased, but temperature of Al_2Cu particles decreased due to the addition of bismuth.

2.2 Gap in Literature

A lot of work has been done in the field of cold chamber high pressure die casting process in different type of process parameters, different type of thermal control factors such as type of cooling, metal temperature, gas entrapment, porosity, effect of addition of material and microstructure. Fast shot velocity and upset pressure are the main factors which affect the density of work material while slow shot velocity has negligible effect on density.

Pouring temperature is the major factor for blow hole defects whereas pouring time and cooling medium are the major factor for bubble defects. Pressure and velocity have no effect on surface hardness and ductility. With increase in pressure or velocity ultimate tensile strength and bulk density increases. However by increasing the squeeze pressure, finer microstructure will be and higher tensile strength obtained. Tensile strength, hardness and impact strength were also affected by applied pressure.

Due to the use of flow distributor and vacuum assist casting, porosity of parts decreases by 90% and 80% ESC is obtained as compare to conventional casting. Porosity of parts decreases with increases in injection pressure, gate velocity, and melting temperature while porosity of parts increases with increase in casting velocity. Shrinkage porosity and pore size distribution also reduces due to the reduction of gate velocity. Delay time has no effect on porosity. Die coating is necessary for easy removal of parts and improve the mechanical properties.

After studying the literature regarding high pressure die casting, the literature reveals that a lot of work has been done on porosity, effect of addition of material, microstructure, interfacial heat transfer coefficient etc but less work has been reported on input factors that have combined effect on responses. No work has been described in literatures which optimize the process parameters of cold chamber high pressure die casting using LM9 and ADC12 aluminium alloys.

2.3 Problem Formulation

Based on the literature survey and the subsequent analysis of gaps the present work aims to investigate the influence of various process parameters on the mechanical properties of LM9 and ADC12 aluminium alloys produced parts by using cold chamber high pressure die casting machine.

The process parameters varied were pouring temperature of molten metal, injection pressure, die holding time and types of die coatings. The responses were density, hardness and surface roughness. The entire experiments were carried out on cold chamber high pressure die casting machine available at central workshop, Thapar University, Patiala.

2.4 Objectives

To investigate the effect of process parameters (pouring temperature of molten metal, injection pressure, die holding time, types of die coatings) on mechanical properties of final product.

1. To investigate the significant interaction between the above factors.
2. To study the microstructure analysis of machined surface.

These objectives have been completed by using box-behnken design technique and scanning electron microscope (SEM).

2.5 Work Plan

Following work have been performed to complete the project:

1. Preparatory work
   a) Selection of raw material for die casting
   b) Preparations of samples on cold chamber high pressure die casting machine
   c) Remove the extra material from the edges of the samples
   d) Machining the samples on grinding machine
2. After finalization of the significant process parameters detailed experiment were carried out with all possible variations
3. Measurements were taken for each input factor and results were analyzed using box-behnken design technique
4. Study of microstructure analysis

Chapter 3

Design of Experiments

3.1 Introduction

High pressure die casting (HPDC) is a superior process for production of various types of engineering products by injecting the molten metal under pressure into reusable mould cavity. Complex shapes casting can be produced by using high pressure die casting. Accurate surface finish and better dimensional accuracy can be achieved by using high pressure die casting. HPDC is suitable for mass production of products [1]. The impact of various input parameters on responses have been studied after machining of die cast products.

The various input parameters were pouring temperature of molten metal, injection pressure, holding time and types of die coating. Experiment was designed by using Design expert software. This software runs the experiments randomly. Box-behnken design technique was used for conducting the experiment. It plays an important role for achieving the high efficiency of the response surface methodology. Box Behnken design experiments require lesser experiments as compare to Central Composite design. The proposed Box Behnken design requires 29 experiments.

3.2 Objective Function

The main purpose of this work to evaluate the effect of process parameters such as pouring temperature of molten metal, injection pressure of molten metal, holding time and types of die coating (silicon oil, transformer oil, transformer oil + graphite) on mechanical properties of the materials such as surface roughness, hardness and density of materials.

3.3 Selection of Factors

Fish bone diagram was used to determine the factors which improve the quality of cast products. It is shown in Figure 3.1. The casting process parameters with their different levels have been selected after exhaustive literature survey. The selected parameters are shown in Table 3.1.

Table 3.1: Selected Factors and their ranges

REPRESENTATION	FACTORS	LEVEL 1	LEVEL 2	LEVEL 3
A	Pouring temperature of molten metal (^{O}C)	760	780	800
B	Injection pressure (kg/cm^2)	150	180	210
C	Die holding time (sec)	7	11	15
D	Types of die coating	Silicon oil	Transformer oil	Transformer oil + Graphite

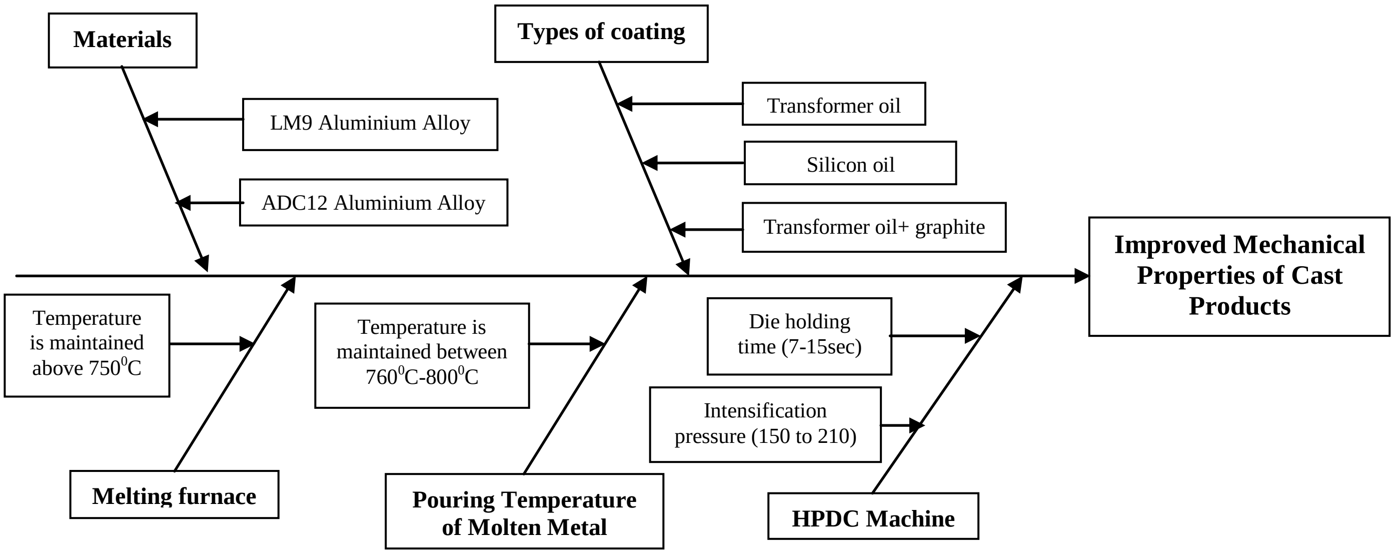

Figure 3.1: Cause and effect diagram of HPDC

3.4 Box-Behnken Design

Box-behnken design technique plays an important role for achieving the high efficiency of the response surface methodology. Response surface methodology (RSM) consists of a group of statistical and mathematical techniques used to optimize the output parameters which is affected by several input parameters. RSM technique is used in designing, developing and analyzing new technical studying and products. It is also an effective technique in development of existing studies and products. It is a cost effective technique [36].

The efficiency of Box-Behnken design is higher for an experiment involving four factors and three levels. Box Behnken design experiments require lesser experiments as compare to Central Composite design. The proposed Box Behnken design requires 29 experiments. Experiments were designed by using Design expert software. This software runs the experiments randomly.

2D and 3D plots of responses were also developed by Design expert software. Such plots clear give an idea of the influence process variable over others; further the plots present the trend of variables interaction in the process. Regression models were developed and its acceptability was validated to forecast the output values at nearly all conditions. Further the models were verified by performing experiments, taking four sets of random input values. The response values measured through experiments are similar with the predicted values using the model. The experimental data collected as per BBD was used.

Table 3.2: Plan of experiments using BBD

Run	A: Pouring temp (°C)	B: Injection pressure (kg/cm2)	C: Holding time (sec)	D: Coating
1	780	210	11	Silicon oil
2	800	210	11	Transformer oil
3	800	180	11	Silicon oil
4	780	150	15	Transformer oil
5	760	180	11	Silicon oil
6	800	180	11	Transformer oil+ Graphite
7	780	180	11	Transformer oil
8	780	180	15	Silicon oil
9	800	180	7	Transformer oil
10	780	180	7	Silicon oil
11	780	150	11	Silicon oil
12	780	210	7	Transformer oil
13	780	180	11	Transformer oil
14	760	150	11	Transformer oil
15	800	180	15	Transformer oil
16	780	210	15	Transformer oil
17	780	210	11	Transformer oil+ Graphite
18	760	180	7	Transformer oil
19	800	150	11	Transformer oil
20	780	180	11	Transformer oil
21	780	180	7	Transformer oil+ Graphite
22	780	180	11	Transformer oil
23	760	210	11	Transformer oil
24	780	150	11	Transformer oil+ Graphite
25	760	180	11	Transformer oil+ Graphite
26	760	180	15	Transformer oil
27	780	150	7	Transformer oil
28	780	180	15	Transformer oil+ Graphite
29	780	180	11	Transformer oil

Box-Behnken design with twenty nine rows and five columns were used in that study. Therefore, twenty nine experiments are required to study the project.

3.5 Description of Cold Chamber Die Casting Machine

Specifications of cold chamber high pressure die casting machine are shown in Table 3.3.

Table 3.3: Specification of cold chamber die casting machine

Locking force	80 tons
Injection force	11.5 tons
Hydraulic ejection force	4 tons
Die mounting plates	520×520 (mm)
Space between tie bars	330×330 (mm)
Max. die height	400 mm
Min. die height	200 mm
Tie bar diameter	60 mm
Die opening stroke	200 mm
Injection plunger stroke	250 mm
Ejection stroke	50 mm
Distance between center and bottom injection	85 mm
Electric motor capacity	5.5 kw
Working pressure	100/135 kg/cm^2
Hydraulic pump (vane type)	70 ltr./min
Oil tank capacity	300 ltr.
Machine weight	3.5 tons
Shot capacity	950 gm

Figure 3.2 shows the horizontal cold chamber high pressure die casting machine used for experimentations. The clamping force of die casting machine is 80 ton. Injection pressure can be set by adjusting the lever fitted on the machine. The instructions to vary die clamping time are given using the Human Machine Interface. The main parts of machine are cover plate, ejector die, injection cylinder, injection rod, die regulating valve, accumulator, oil tank, back plate and pressure regulating valve. Die casting machine can be operated on manual as well as automatic mode according to the requirements.

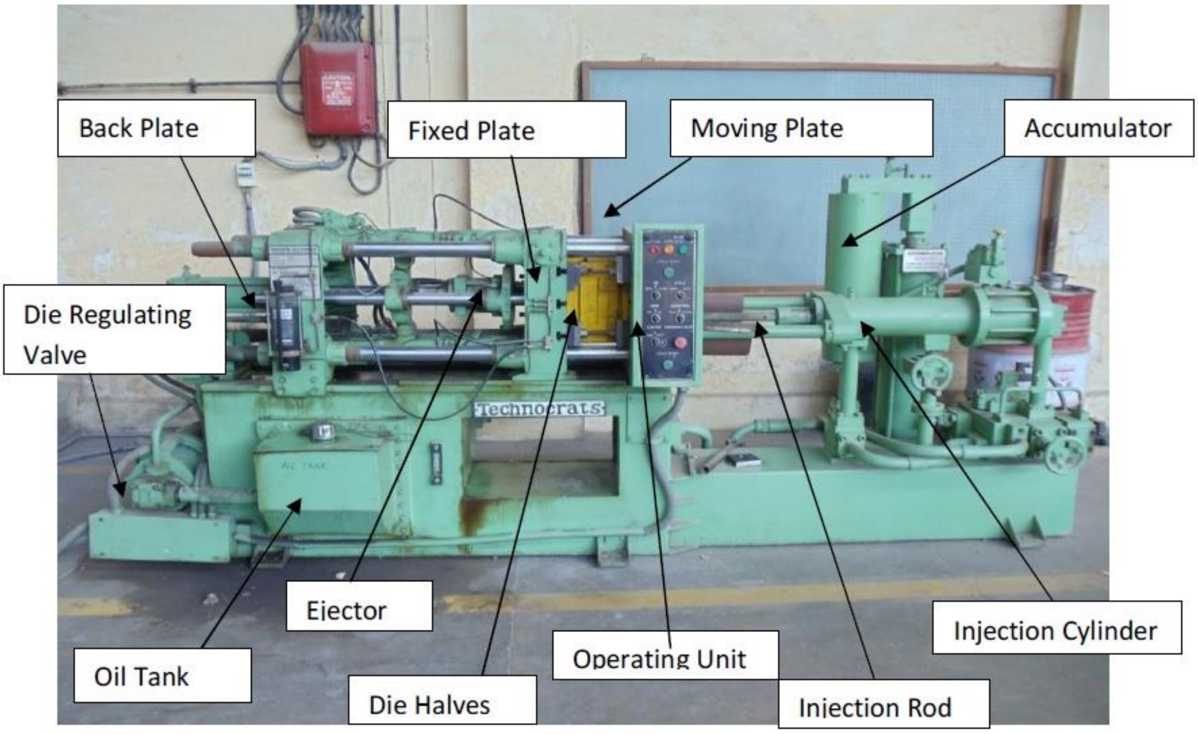

Figure 3.2: High pressure cold chamber die casting machine 80 tons (Courtesy: Thapar University, Patiala)

3.5.1 Operating Mode

- **Manual mode:** In this mode machine is operated by the operator. Die open and closing time is depending on the operator.
- **Automatic mode:** In this mode machine is operated by control panel mounted on the front of machine. Die opening time, die closing time and casting ejection time operated by control panel.
- **Stop button:** Stop button is used to stop the entire process.

- **3.5.2 Display Indication**
- **Pressure gauge**: Pressure gauge is used to indicate the injection pressure of molten metal.
- **Pyrometer indicator:** Pyrometer indicator is used to indicate the temperature of molten metal.

3.6 Description of Muffle Furnace

Raw materials were melted in an electric resistance furnace according to the requirement of pouring temperature of molten metal. Figure 3.3 shows the muffle furnace used for melting the raw materials available at Central Workshop, Thapar University Patiala. The maximum temperature range of molten metal is about 1100^0C.

Figure 3.3: Muffle furnace (Courtesy: Thapar University, Patiala)

3.7 Experimental Set Up

In the current investigation, Effect of various die casting process parameters was studied. The process parameters were pouring temperature of molten metal, injection pressure, die holding time and types of die coating. LM 9 and ADC 12 aluminium alloys were used as raw materials. 80 ton clamping force horizontal cold chamber pressure die casting machine was used to manufacture the products. The clamping force of die casting machine is 80 ton. Injection pressure can be set by adjusting the lever fitted on the machine. Injection pressure was varied from 150 to 210 kg/cm^2 as per experimental design. The instruction to vary die clamping time is given using the Human Machine Interface, which was varied from 7 to 15 sec.

Pouring temperature of molten metal varied from 760 to 800^0C, this molten metal is poured into shot sleeve through pouring spoon. Three types of die coatings namely Transformer oil, Silicone oil, Transformer oil + Graphite were used in proposed work. Experiments were conducted as per box-behnken design (BBD). All the trail conditions using BBD are listed in Table 3.2. The entire experiments were carried out in Central Workshop, Thapar University Patiala.

3.7.1 Die Used For Experiment

Dies plays an important role for casting of parts. It is mainly consist of two parts ejector die and cover die. Dies are made up of alloy tool steels like H 13 tool steel. Ejector pins are located on ejector die or movable die halves, which are used for easy removal of die cast parts and allow for cooling and lubricant. Gating and runner system are attached to the cover die or fixed die.

Figure 3.4: Photograph of H13 tool steel die clutch plate (Courtesy: Thapar University, Patiala)

Molten metal enters into die cavity through sprue hole in cover die. When both ejector die and cover die are in close contact, hydraulic pressure is exerted by machine for tight contact between dies. Figure 3.4 shows the multiple cavity die used in experiment available at Central Workshop, Thapar University, Patiala.

3.8 Measuring and Test Equipments Used after Experiments

Density, Hardness and Surface Roughness test were performed on all the samples of ADC12 and LM9 aluminium alloys. The test equipments used for measurement of these responses are given below:

3.8.1 Density Test

Density was measured by using the electronic weighing machine to calculate the mass of casting and micrometer to calculate the volume of casting. Weighing machine used for measurement the weight of casting is shown in Figure 3.5.

Figure 3.5: Weighing Machine (Courtesy: Thapar University, Patiala)

3.8.2 Hardness Test

Hardness of casting was measured on Rockwell hardness tester machine as shown in Figure 3.6. It is depends upon the indentation diameter on the casting. Pyramid shaped steel ball indenter with minor load of 10 kg on B scale for 10 sec was used for measuring the hardness.

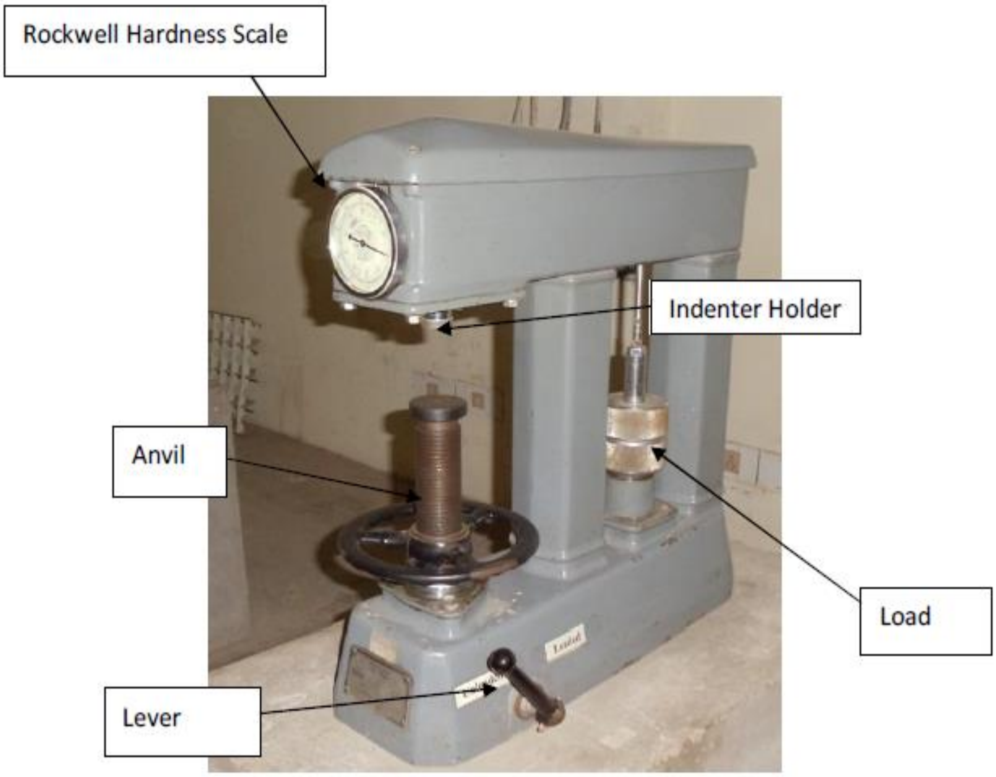

Figure 3.6: Rockwell hardness testing machine model AVERY 6402 (Courtesy: Thapar University, Patiala)

3.8.3 Surface Roughness Tester

Figure 3.7: Surface Roughness tester Mitutoyo model SJ-400 (Courtesy: Thapar University, Patiala)

Mitutoyo model SJ-400 tester was used for measurement of surface roughness as shown in Figure 3.7. The tester uses a stylus method of measurement. Tester has a profile resolution of 12nm and surface roughness can be measure upto 100µm. In this experiment tracing length of 4.8 mm was used.

3.9 Composition of work materials

LM9 and ADC12 Aluminium alloy was used for experimental work. The percentage composition of LM9 and ADC12 Aluminium alloy is shown in Table 3.4. The ingot of both alloys is shown in Fig 3.8. Figure 3.9 shows the final samples after casting.

Table 3.4: Chemical composition of ADC12 and LM9 aluminium alloy

Alloy	Cu	Si	Fe	Mn	Mg	Ni	Zn	Sn	Pb	Ti	Al
LM9 Aluminium Alloy	0.1%	13%	0.6%	0.7%	0.5%	0.1%	0.1%	-	0.1%	0.2%	86.13%
ADC12 Aluminium Alloy	3.2%	9%	0.8%	0.5%	0.2%	0.5%	0.8%	0.2%	-	-	84.8%

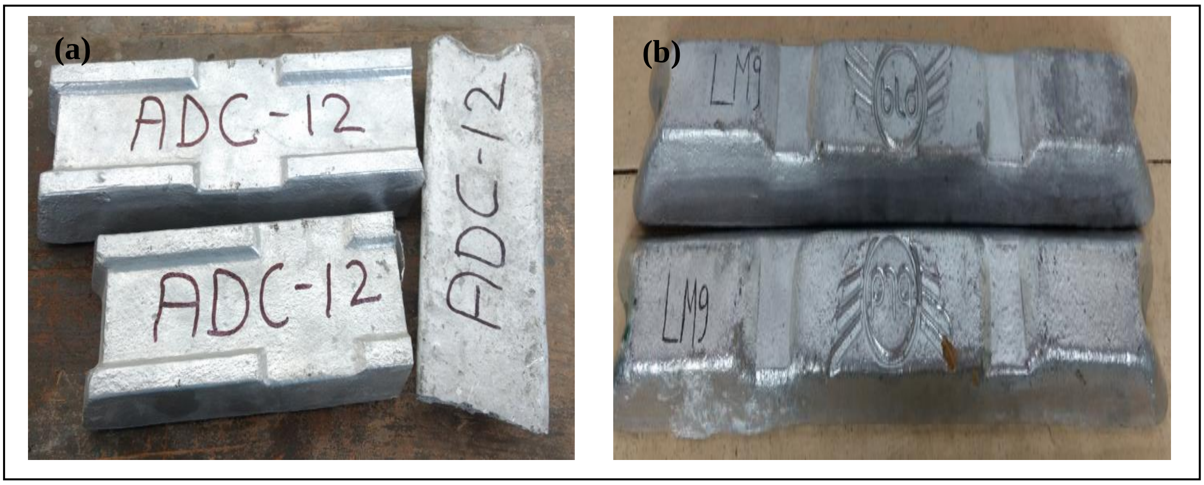

Figure 3.8: Ingot of (a) ADC12 aluminium alloy and (b) LM9 aluminium alloy

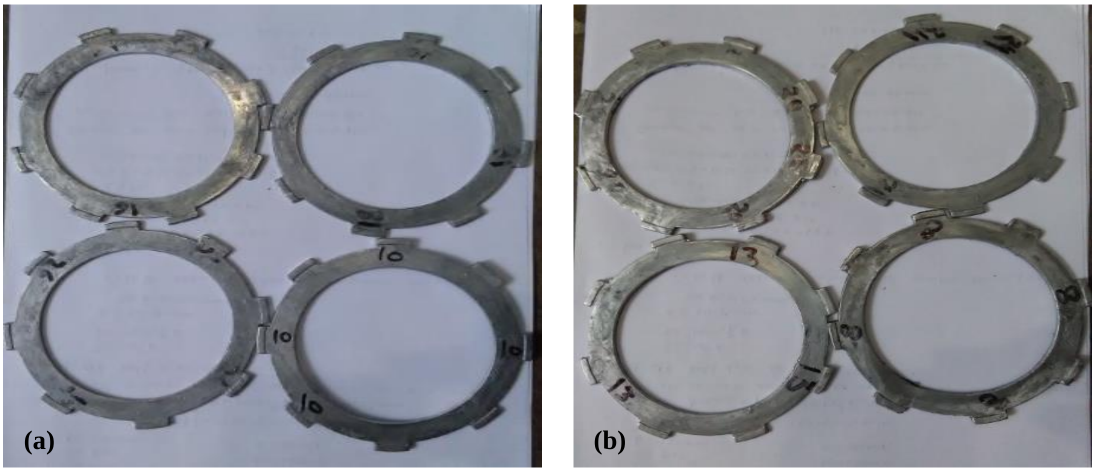

Figure 3.9: Final cast specimens of (a) ADC12 aluminium alloy and (b) LM9 aluminium alloy

3.10 Analysis of results

The experimental data collected as per BBD was used. The result of Density, Hardness, Surface Roughness for LM9 and ADC12 aluminium alloys are shown in Table 3.5&3.6 respectively.

Table 3.5: Experimental obtained values of Response density, Hardness and Surface roughness of LM9 aluminium alloy

Run	A: Pouring Temp (°C)	B: Injection Pressure (kg/cm2)	C: Holding Time(sec)	D: Die Coating	Response Density (gms/mm3)	Response Hardness (HRB)	Response Surface Roughness (μm)
1	780	210	11	Silicon oil	2.8	78	0.77
2	800	210	11	Transformer oil	2.75	80.33	0.55
3	800	180	11	Silicon oil	2.4	70	1.23
4	780	150	15	Transformer oil	2.45	86	1.098
5	760	180	11	Silicon oil	2.6	80	0.67
6	800	180	11	Transformer oil+ Graphite	2.55	76	1.3
7	780	180	11	Transformer oil	2.5	85	0.82
8	780	180	15	Silicon oil	2.55	88	0.84
9	800	180	7	Transformer oil	2.1	72	1.12

10	780	180	7	Silicon oil	2.4	75	1.5
11	780	150	11	Silicon oil	2.4	80	1.37
12	780	210	7	Transformer oil	2.75	87	0.8
13	780	180	11	Transformer oil	2.5	86.33	0.84
14	760	150	11	Transformer oil	2.5	83	0.92
15	800	180	15	Transformer oil	2.55	80	0.8
16	780	210	15	Transformer oil	2.8	91	0.5
17	780	210	11	Transformer oil+ Graphite	2.9	88	1.1
18	760	180	7	Transformer oil	2.58	75	0.86
19	800	150	11	Transformer oil	2.1	68	1.16
20	780	180	11	Transformer oil	2.5	84	0.84
21	780	180	7	Transformer oil+ Graphite	2.45	86	1.53
22	780	180	11	Transformer oil	2.5	86.67	0.84
23	760	210	11	Transformer oil	2.7	81	0.32
24	780	150	11	Transformer oil+ Graphite	2.5	78	1.71
25	760	180	11	Transformer oil+ Graphite	2.8	78	1.35
26	760	180	15	Transformer oil	2.65	84	0.56
27	780	150	7	Transformer oil	2.35	78	1.42
28	780	180	15	Transformer oil+ Graphite	2.7	87.4	1.51
29	780	180	11	Transformer oil	2.6	87	0.84

Table 3.6: Experimental obtained values of Response density, Hardness and Surface roughness of ADC12 aluminium alloy

Run	A: Pouring Temp (°C)	B: Injection Pressure (kg/cm2)	C: Holding Time(sec)	D: Die Coating	Response Density (gms/mm3)	Response Hardness (HRB)	Response Surface Roughness (µm)
1	780	210	11	Silicon oil	2.8	82	0.42
2	800	210	11	Transformer oil	2.75	82.3	0.57
3	800	180	11	Silicon oil	2.4	81	1
4	780	150	15	Transformer oil	2.45	83.5	1.25
5	760	180	11	Silicon oil	2.6	83	0.488
6	800	180	11	Transformer oil+ Graphite	2.55	82	1.3
7	780	180	11	Transformer oil	2.5	85.5	0.9
8	780	180	15	Silicon oil	2.55	80	0.6
9	800	180	7	Transformer oil	2.14	80	1.3
10	780	180	7	Silicon oil	2.42	81.5	1.4
11	780	150	11	Silicon oil	2.39	77	1.6
12	780	210	7	Transformer oil	2.73	85	0.9
13	780	180	11	Transformer oil	2.52	85.2	0.839
14	760	150	11	Transformer oil	2.52	80.67	1.1
15	800	180	15	Transformer oil	2.54	83	0.65
16	780	210	15	Transformer oil	2.82	84	0.52
17	780	210	11	Transformer oil+ Graphite	2.92	84	1.3
18	760	180	7	Transformer oil	2.58	83.8	0.7
19	800	150	11	Transformer oil	2.1	78	1.2
20	780	180	11	Transformer oil	2.5	85.7	0.8
21	780	180	7	Transformer oil+ Graphite	2.6	80	1.5
22	780	180	11	Transformer oil	2.5	84.5	0.8

23	760	210	11	Transformer oil	2.7	88	0.34
24	780	150	11	Transformer oil+ Graphite	2.51	83	1.55
25	760	180	11	Transformer oil+ Graphite	2.8	86	1.4
26	760	180	15	Transformer oil	2.65	86	0.657
27	780	150	7	Transformer oil	2.35	76	1.5
28	780	180	15	Transformer oil+ Graphite	2.7	88	1.6
29	780	180	11	Transformer oil	2.56	83.8	0.839

3.11 Response characteristics

Response Characteristics of this experimental work is shown in Table 3.7. Die casting parts should have higher Density and Hardness values but lower Surface Roughness values.

Table 3.7: Response Characteristics

Response name	Response type	Units
Density	Higher is better	g/mm^3
Hardness	Higher is better	HRB
Surface Roughness	Lower is better	Microns

Chapter 4

Results and Analysis

4.1 Introduction

The effect of various process parameters such as pouring temperature of molten metal, injection pressure, die holding time and types of die coating (Transformer oil, Silicone oil, Transformer oil + Graphite) on mechanical properties such as density, hardness, surface roughness has been studied in the present work. ADC12 and LM9 Aluminium alloy was used for this experimental work.

Design Expert software was used for experimental work. In this proposed investigation all the four factors were varied at three levels. After conducting the 29 trials the mean value of all the factors are tabulated.

4.2 Analysis of LM 9 Aluminium Alloy

The experimental data collected as per BBD was used.

4.2.1 Results of Density

Density of casting was measured by using the weighing machine to measure the weight of casting and micrometer to measure the volume of casting.

$$Density\ is\ given\ by\ \rho = weight\ of\ casting \div volume\ of\ casting \quad (4.1)$$

The equation developed for response density is given below:

$$\mathbf{Mean\ Density} = -3.13339 + 0.06731 \times A - 0.16227 \times B - 0.86448 \times C + 0.21792 \times D - 0.00007 \times A \times A + 0.00006 \times B \times B - 0.00151 \times C \times C + 0.06583 \times D \times D + 0.00018 \times A \times B + 0.00118 \times A \times C - 0.00062 \times A \times D - 0.00010 \times B \times C + 0.00625 \times C \times D \quad (4.2)$$

Table 4.1: ANOVA table for density

Source	Sum of square	DF	Mean Square	F Value	Prob. >F	%age Contribution	Status
Model	.94	8	.067	16.63	< 0.0001		Significant
A	.16	1	.16	39.24	< 0.0001	18.9	Significant
B	.48	1	.48	118.68	< 0.0001	56.7	Significant
C	. 095	1	.095	23.59	0.0003	11.22	Significant
D	.047	1	.047	11.59	0.0043	5.552	Significant
A^2	0.006	1	0.006	1.48	0.2433	0.709	Not Significant
B^2	.023	1	.023	5.69	0.0317	2.717	Significant
C^2	0.003788	1	0.003788	0.94	0.3496	0.447	Not Significant
D^2	.028	1	.028	6.95	0.0195	3.308	Significant
AB	.051	1	.051	12.52	0.0033	6.025	Significant
AC	.036	1	.036	8.93	0.0098	4.253	Significant
AD	0.0006250	1	0.000625	0.15	0.7002	0.074	Not Significant
BC	0.0006250	1	0.000625	0.15	0.7002	0.074	Not Significant
BD	0	1	0	0	1.0000	0	Not Significant
CD	0.0025	1	0.0025	0.62	0.4449	0.295	Not Significant
Residual	.057	14	0.004045				
Lack of Fit	.049	10	0.004863	2.43	.2032		Not Significant
Pure Error	.008	4	0.002			0.945	
Cor Total	1	28					

Significant Factor*:* A, B, C, D, B^2, D^2, AB, AC

Insignificant factor*:* A^2, C^2, AD, BC, BD, CD

In this experiment F-value of the model is 16.63. This signifies that model is significant. There is only a 0.01% chance that a model with this large value could occur due to noise.

If values of "Prob > F" is less than 0.05, this indicate factors are significant. If this value is greator than 0.05 , this indicate factors are not significant. If there are many insignificant factors (not counting those required to support hierarchy), model reduction may improve your model.

In this experiment F-value of Lack of Fit is 2.43, this indicate that Lack of Fit is not significant relative to the pure error. There is a 20.32% chance that a "Lack of Fit F-value" this large could occur due to noise.

The "Pred R-Squared value" of 0.7069 is in reasonable agreement with the "Adj R-Squared value" of 0.8866. Signal to noise ratio is measured by "Adeq Precision". A ratio greater than 4 is desirable. In this experiment signal to noise ratio of 17.190 indicate an adequate signal.

Table 4.2: ANOVA parameters

Std. Dev.	.064	R-Squared	0.9433
Mean	2.55	Adj R-Squared	0.8866
C.V.	2.49	Pred R-Squared	0.7069
PRESS	0.29	Adeq Precision	17.190

Coefficient of Variation (C.V.) Press: predicated residual sum of squares; Std. Dev.: standard deviance.

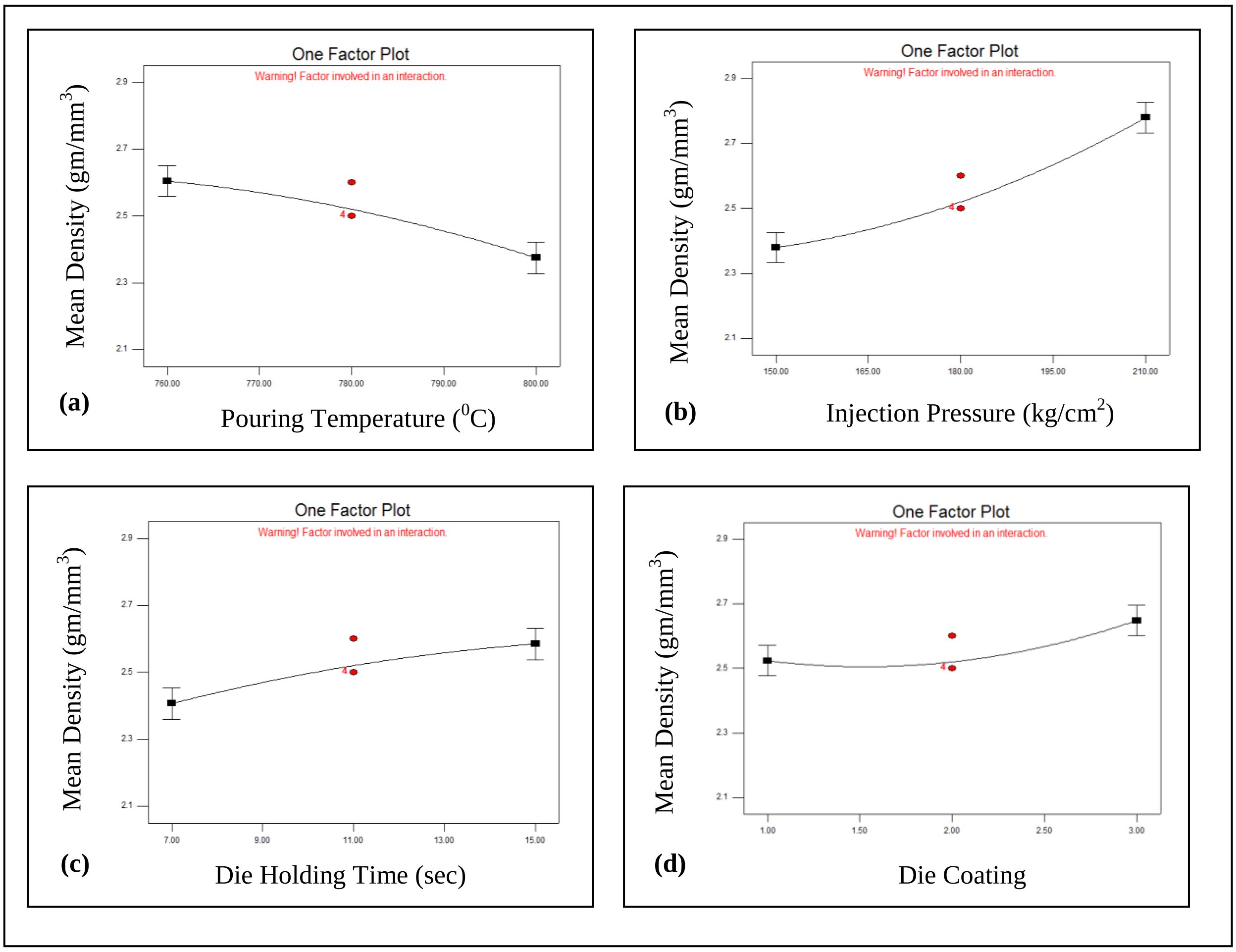

Figure 4.1: Variation of (a) pouring temperature v/s density, (b) injection pressure v/s density, (c) die holding time v/s density and (d) die coating v/s density.

Pouring temperature of molten metal, injection pressure, die holding time and die coating are the significant factors which influence the casting density as shown in Figure 4.1.

Injection pressure is the prominent factor which affects the casting density. When injection pressure increases, cooling rate of liquid phase increases due to the compaction action. This result indicates the decrease in porosity formation. It was observed that density of casting increases, when pouring temperature decreases (Figure 4.1a), injection pressure increases (Figure 4.1b) and holding time increases (Figure 4.1c).

Density of die cast parts increases with decrease in pouring temperature due to the reduction in gas porosity. In figure 4.1d silicon oil, transformer oil and transformer oil + graphite are represented on the graph horizontal axis as 1, 2 and 3 respectively. Figure 4.1d shows that with addition of graphite in transformer oil density of casting increases.

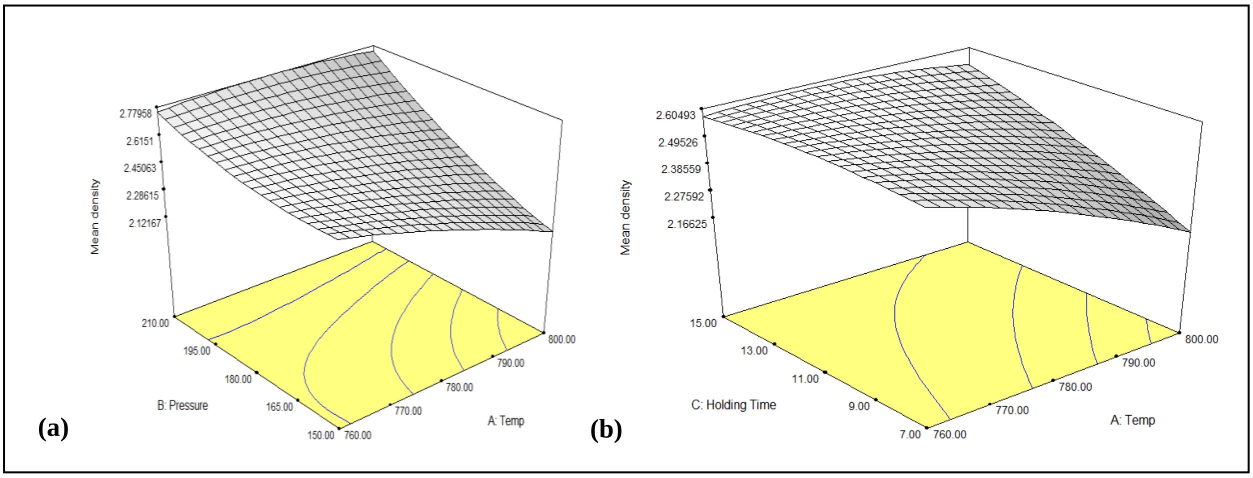

Figure 4.2: 3D plot showing variation of (a) density value with pouring temperature and injection pressure and (b) density value with pouring temperature and die holding time.

The 3D plots for the effect of pouring temperature and injection pressure, pouring temperature and holding time on density of die cast components are shown in Figure 4.2a & 4.2b respectively.

Effect of pouring temperature of molten metal and injection pressure on casting density at different process parameters is shown in Figure 4.2a. The density of casting increases with an increase in pouring temperature at high pressure. The density of casting decreases with increase in temperature at low pressure. Effect of pouring temperature of molten metal and die holding time on casting density at different process parameters is shown in Figure 4.2b. The density of casting increases with an increase in holding time at desired temperature.

4.2.2 Result of Hardness

Hardness of casting was measured on Rockwell hardness tester machine. It is depends upon the indentation diameter on the casting. Pyramid shaped steel ball indenter with minor load of 10 kg on B scale for 10 s was used for measuring the hardness.

The equation developed for response hardness is given below:

$$\begin{aligned}\textit{Response Hardness} &= -10143.9833 + 27.4329 \times A - 4.2701 \times B + 5.7835 \times C - 75.1366 \times D \\ &- 0.0184 \times A \times A - 0.0012 \times B \times B + 0.0230 \times C \times C - 2.7554 \times D \times D \\ &+ 0.0059 \times A \times B - 0.0031 \times A \times C + 0.1000 \times A \times D - 0.0083 \times B \times C \\ &+ 0.1000 \times B \times D - 0.7250 \times C \times D \qquad (4.3)\end{aligned}$$

Table 4.3: ANOVA table for Hardness

Source	Sum of square	DF	Mean Square	F Value	Prob. >F	%age Contribution	Status
Model	921.74	14	65.84	21.97	< 0.0001		Significant
A	100.17	1	100.17	33.42	< 0.0001	10.6	Significant
B	87.1	1	87.1	29.06	< 0.0001	9.221	Significant
C	156.96	1	156.96	52.37	< 0.0001	16.62	Significant
D	41.81	1	41.81	13.95	0.0022	4.426	Significant
A^2	354.16	1	354.16	118.16	< 0.0001	37.49	Significant
B^2	6.67	1	6.67	2.23	0.1579	0.706	Not Significant
C^2	0.89	1	0.89	0.3	0.5952	0.094	Not Significant
D^2	49.25	1	49.25	16.43	0.0012	5.214	Significant
AB	51.34	1	51.34	17.13	0.0010	5.435	Significant
AC	0.25	1	0.25	0.083	0.777	0.026	Not Significant
AD	16	1	16	5.34	0.0366	1.694	Significant
BC	4	1	4	1.33	0.2673	0.423	Not Significant
BD	36	1	36	12.01	0.0038	3.811	Significant
CD	33.64	1	33.64	11.22	0.0048	3.561	Significant
Residual	41.96	14	3				
Lack of Fit	35.6	10	3.56	2.24	.2271		Not Significant
Pure Error	6.36	4	1.59			0.673	
Cor Total	963.7	28					

***Significant Factor**:* A, B, C, D, D^2, AB, AC, BD, CD

***Insignificant factor**:* B^2, C^2, AC, BC

In this experiment F-value of the model is 21.97. This signifies that model is significant. There is only a 0.01% chance that a model with this large value could occur due to noise.
If values of "Prob > F" is less than 0.05 , this indicate factors are significant. If this value is greator than 0.05, this indicate factors are not significant. If there are many insignificant factors (not counting those required to support hierarchy), model reduction may improve your model. In this experiment F-value of Lack of Fit is 2.24, this indicate that Lack of Fit is not significant relative to the pure error. There is a 22.71% chance that a "Lack of Fit F-value" this large could occur due to noise.
The "Pred R-Squared value" of 0.7769 is in reasonable agreement with the "Adj R-Squared value" of 0.9129. Signal to noise ratio is measured by "Adeq Precision". A ratio greater than 4 is desirable. In this experiment signal to noise ratio of 17.858 indicate an adequate signal.

Table 4.4: ANOVA parameters

Std. Dev.	1.73	R-Squared	0.9565
Mean	81.34	Adj R-Squared	0.9129
C.V.	2.13	Pred R-Squared	0.7769
PRESS	215.02	Adeq Precision	17.858

Coefficient of Variation (C.V.) Press: predicated residual sum of squares; Std. Dev.: standard deviance.
The effect of pouring temperature of molten metal, injection pressure, die holding time and die coating on hardness at different process parameter is shown in Figure 4.3a, 4.3b, 4.3c & 4.3d respectively.
Holding time is the outstanding parameter that affects the hardness of die cast parts. Hardness value of LM9 aluminium alloy increases, when temperature increase from 760°C to 780°C and hardness value decreases if temperature increase beyond 780°C (Figure 4.3a). Hardness of LM9 aluminium alloy increases with increase in injection pressure and die holding time as shown in Figure 4.3b & 4.3c respectively. In figure 4.3d silicon oil, transformer oil and transformer oil + graphite are represented on the graph horizontal axis as 1, 2 and 3 respectively. If die is coated with transformer oil in place of silicon oil, hardness of die cast component increases (Figure 4.3d). Due to increase in cooling rate hardness of die cast parts increases with increase in injection pressure.

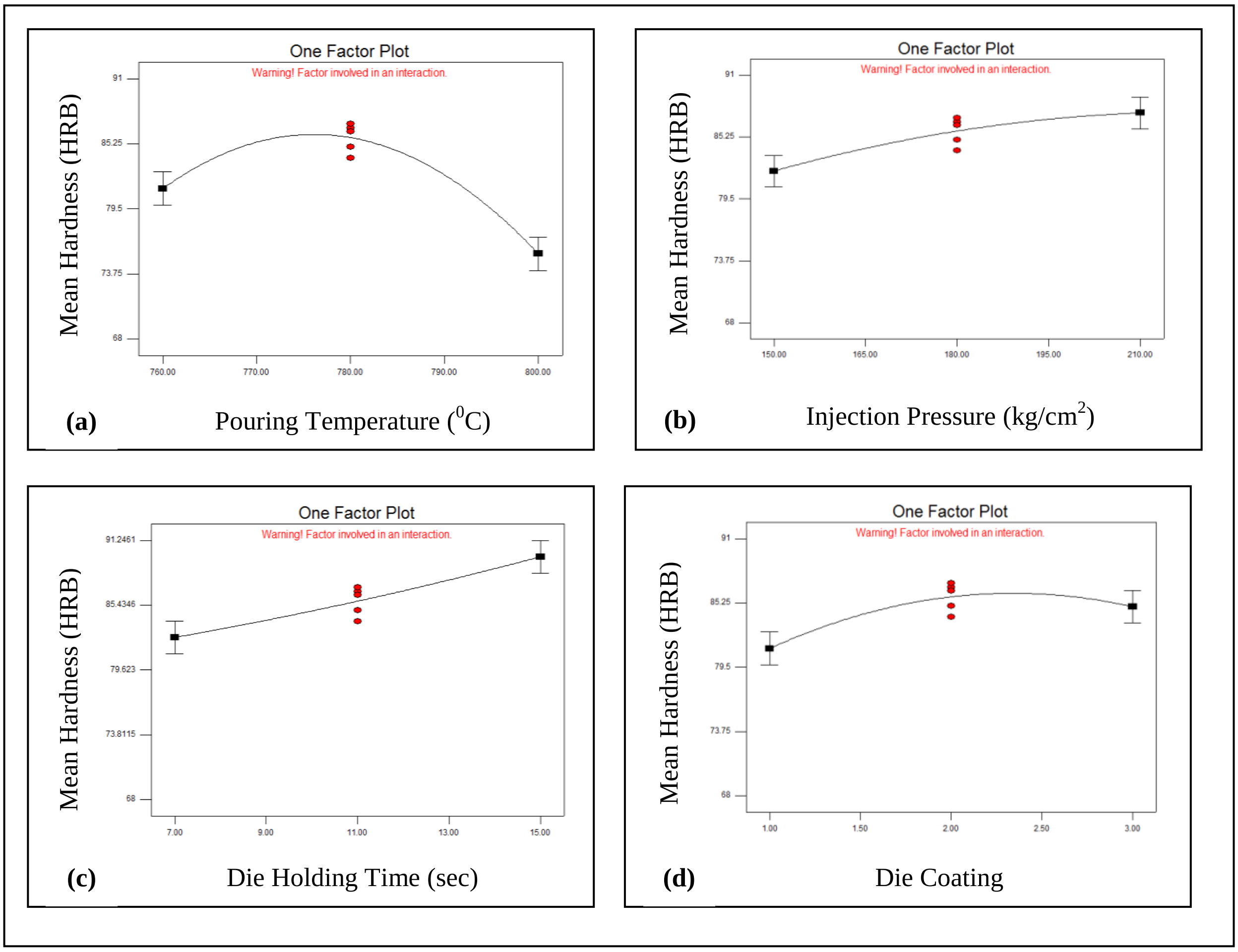

Figure 4.3: Variation of (a) pouring temperature v/s hardness, (b) injection pressure v/s hardness, (c) die holding time v/s hardness, and (d) die coating v/s hardness.

The 3D plots for the effect of pouring temperature and injection pressure, pouring temperature and die coating, pressure and die coating, holding time and die coating on hardness of die cast components are shown in Figure 4.4a, 4.4b, 4.4c & 4.4d.

Hardness value of LM9 aluminium alloy increases with increase in pressure at desired temperature and it is minimum at high temperature and low pressure (Figure 4.4a). In figure 4.4b, 4.4c and 4.4d silicon oil, transformer oil and transformer oil + graphite die coating materials are represented on the graphs as 1, 2 and 3 respectively. Hardness value is minimum at high temperature with silicon oil is used as die coating material (Figure 4.4b).

Increasing the injection pressure with transformer oil + graphite was used as a die coating material, hardness of die cast component increases and hardness of die cast component decreases with minimizing holding time and silicon oil was used as die coating material are illustrate in Figure 4.4c & 4.4d.

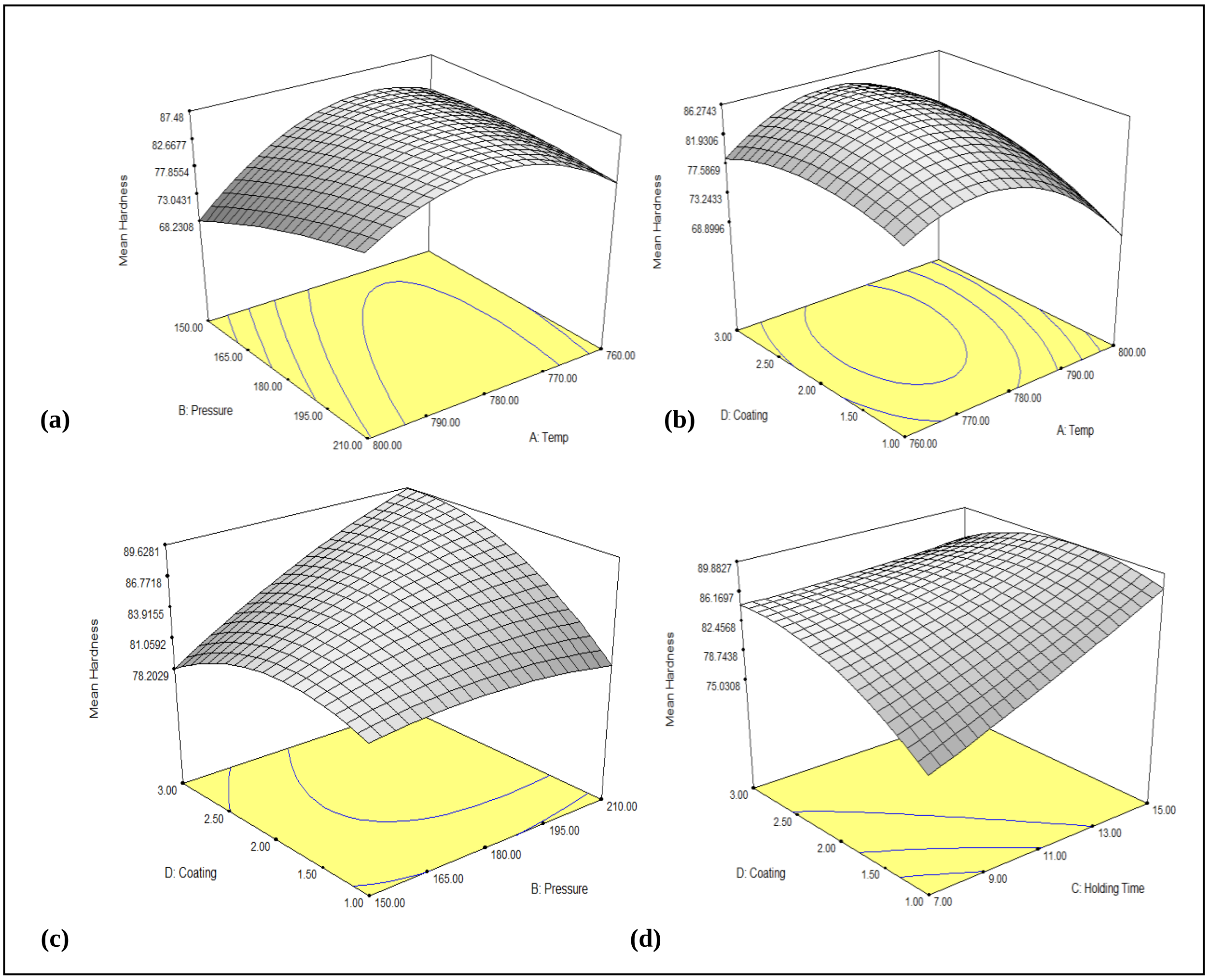

Figure 4.4: 3D plot showing variation of (a) hardness value with pouring temperature and injection pressure, (b) hardness value with pouring temperature and die coating, (c) hardness value with injection pressure and die coating and (d) hardness value with die holding time and die coating.

4.2.3 Result of Surface Roughness

Mitutoyo model SJ-400 tester was used for measurement of surface roughness. The tester uses a stylus method of measurement. Tester has a profile resolution of 12nm and surface roughness can be measure upto 100µm. In this experiment tracing length of 4.8 mm was used.

The equation developed for response surface roughness is given below:

$$\begin{aligned}\boldsymbol{Mean\ Surface\ Roughness} \\ &= -169.95916 + 0.42910 \times A - 0.00942 \times B - 0.22816 \times C + 4.09538 \times D \\ &- 0.00026 \times A \times A + 0.000006 \times B \times B + 0.00678 \times C \times C + 0.40083 \times D \times D \\ &- 0.000004 \times A \times B - 0.00006 \times A \times C - 0.00762 \times A \times D + 0.00004 \times B \times C \\ &- 0.00008 \times B \times D + 0.04000 \times C \times D \end{aligned} \quad (4.4)$$

Table 4.5: ANOVA table for Surface Roughness

Source	Sum of square	DF	Mean Square	F Value	Prob. >F	%age Contribution	Status
Model	3.47	14	0.25	1491.1	< 0.0001		Significant
A	0.18	1	0.18	1099.13	< 0.0001	5.39	Significant
B	1.1	1	1.1	6641.24	< 0.0001	32.94	Significant
C	0.31	1	0.31	1853.66	< 0.0001	9.282	Significant
D	0.37	1	0.37	2255.25	< 0.0001	11.08	Significant
A^2	0.07	1	0.07	423.81	< 0.0001	2.096	Significant
B^2	0.0002	1	0.0002	1.22	0.2884	0.006	Not Significant
C^2	0.076	1	0.076	456.28	< 0.0001	2.276	Significant
D^2	1.04	1	1.04	6275.41	< 0.0001	31.14	Significant
AB	0.00002	1	0.00025	0.15	0.7039	7E-04	Not Significant
AC	0.0001	1	0.0001	0.6	0.4507	0.003	Not Significant
AD	0.093	1	0.093	560.15	< 0.0001	2.785	Significant
BC	0.00012	1	0.00012	0.73	0.4077	0.004	Not Significant
BD	0.00002	1	0.00002	0.15	0.7039	7E-04	Not Significant
CD	0.1	1	0.1	616.6	< 0.0001	2.994	Significant
Residual	0.00233	14	0.00016				
Lack of Fit	0.00201	10	0.0002	2.51	.1949		Not Significant
Pure Error	0.00032	4	0.00008			0.01	
Cor Total	3.47	28					

***Significant Factor**:* A, B, C, D, A^2, C^2, D^2, AD, CD

***Insignificant factor**:* B^2, AB, AC, BC, BD

In this experiment F-value of the model is 1491.1. This signifies that model is significant. There is only a 0.01% chance that a model with this large value could occur due to noise.

If values of "Prob > F" is less than 0.05 , this indicate factors are significant. If this value is greator than 0.05, this indicate factors are not significant. If there are many insignificant factors (not counting those required to support hierarchy), model reduction may improve your model. In this experiment F-value of Lack of Fit is 2.51, this indicate that Lack of Fit is not significant relative to the pure error. There is a 19.49% chance that a "Lack of Fit F-value" this large could occur due to noise.

The "Pred R-Squared value" of 0.9665 is in reasonable agreement with the "Adj R-Squared value" of 0.9787. Signal to noise ratio is measured by "Adeq Precision". A ratio greater than 4 is desirable. In this experiment signal to noise ratio of 152.277 indicate an adequate signal.

Table 4.6: ANOVA parameters

Std. Dev.	0.013	R-Squared	0.9893
Mean	1.01	Adj R-Squared	0.9787
C.V.	1.28	Pred R-Squared	0.9665
PRESS	0.012	Adeq Precision	152.277

Coefficient of Variation (C.V.) Press: predicated residual sum of squares; Std. Dev.: standard deviance.

The effect of pouring temperature of molten metal, injection pressure, die holding time and die coating on surface roughness at different process parameter is shown in Figure 4.5a, 4.5b, 4.5c &4.5d respectively.

Injection pressure is the main factor which affects the surface roughness of die cast products. It was observed that surface roughness value of LM9 aluminium alloy decreases with decrease in pouring temperature (Figure 4.5a). Surface roughness values increases with decrease in injection pressure and holding time is shown in Figure 4.5b & 4.5c respectively.

In figure 4.5d silicon oil, transformer oil and transformer oil + graphite are represented on the graph horizontal axis as 1, 2 and 3 respectively. If die is coated with transformer oil in place of mixture of transformer oil and graphite, surface roughness of die cast component decreases (Figure 4.5d).

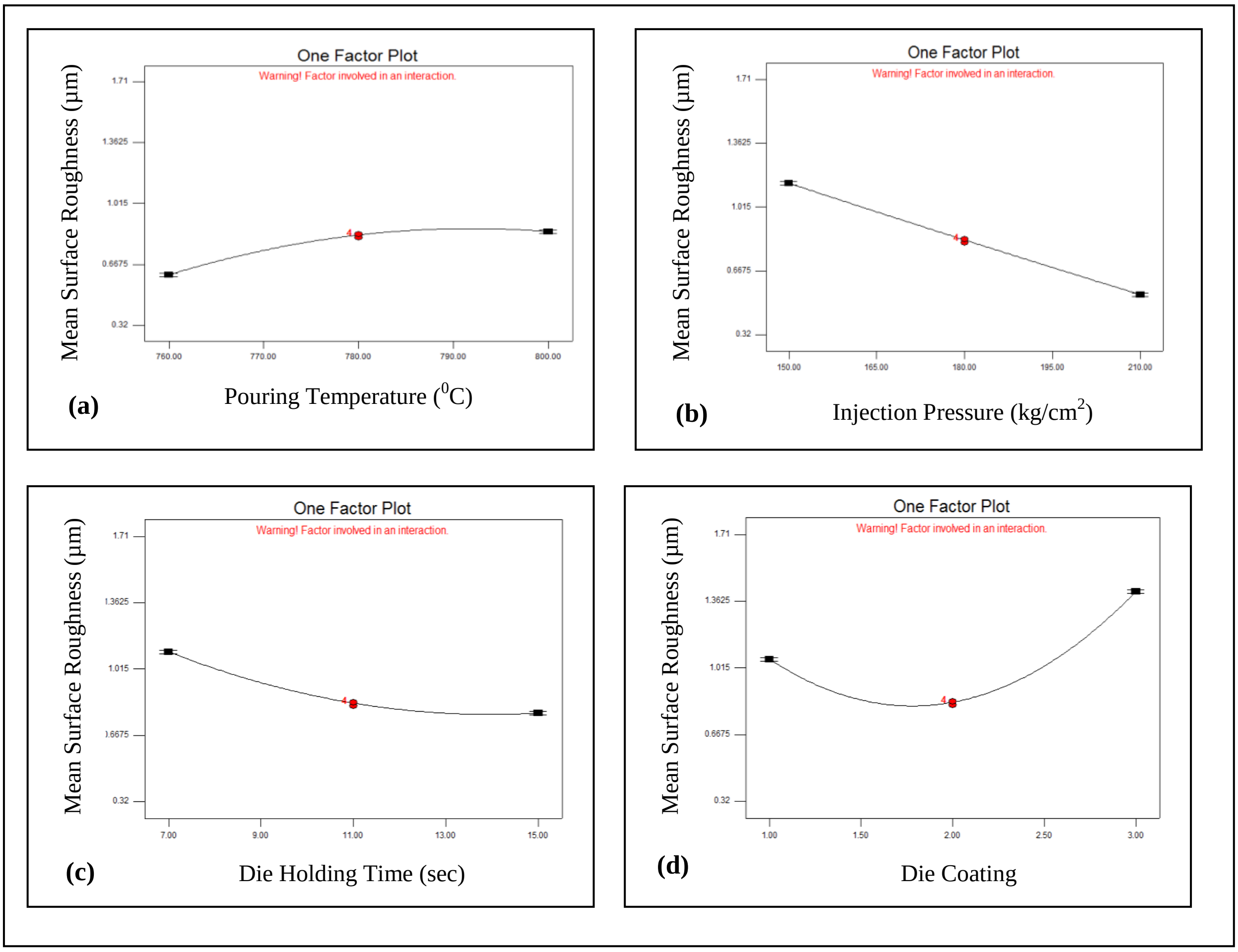

Figure 4.5: Variation of (a) pouring temperature v/s surface roughness, (b) injection pressure v/s surface roughness, (c) die holding time v/s surface roughness and (d) die coating v/s surface roughness.

The 3D plots for the effect of pouring temperature and die coating, holding time and die coating on surface roughness of die cast components is shown in Figure 4.6a & 4.6b respectively.

In figure 4.6a and 4.6b silicon oil, transformer oil and transformer oil + graphite are represented on the graph as 1, 2 and 3 respectively. The surface roughness of die cast parts decreases with decrease in pouring temperature when die is coated with silicon oil. Lowest surface roughness value was obtained at low pouring temperature and transformer oil as coating for the die surface as shown in Figure 4.6a.

The surface roughness of die cast parts decreases with increase in holding time when die is coated with silicon oil or transformer oil (Figure 4.6b). Lowest surface roughness value was obtained at high holding time and dies coated with transformer oil.

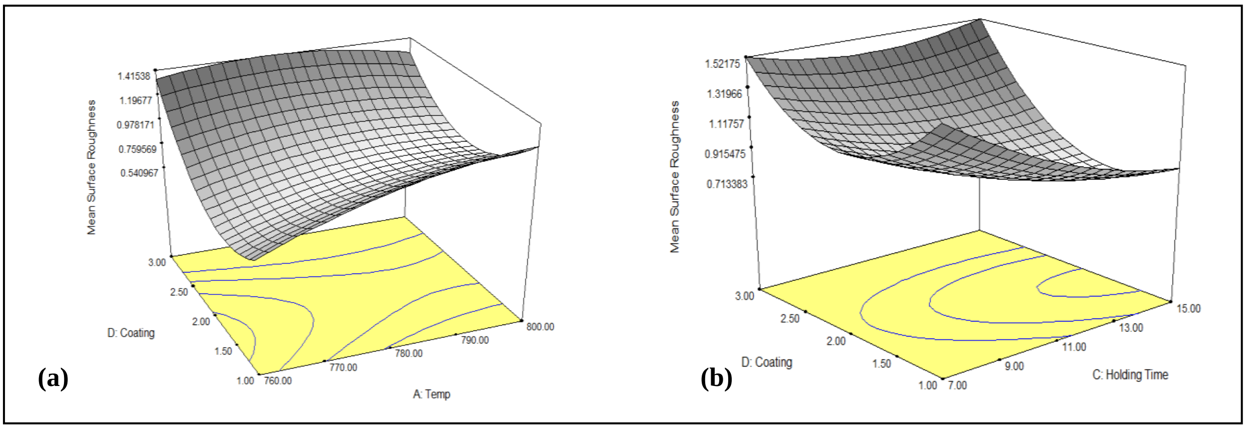

Figure 4.6: 3D plot showing variation of (a) surface roughness value with pouring temperature and die coating and (b) surface roughness value with die holding time and die coating.

4.2.4 SEM Study of Surface Quality

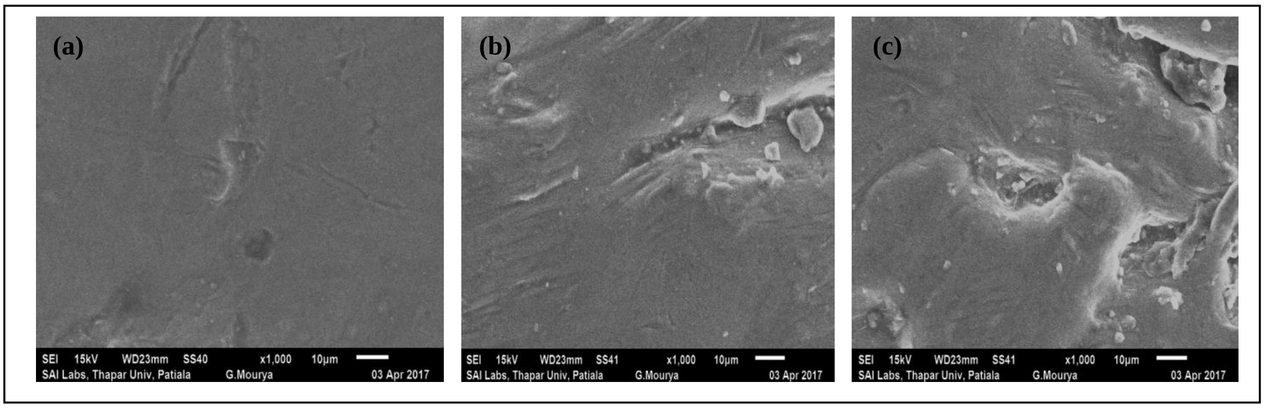

Figure 4.7: Surface quality obtained through HPDC of LM9 aluminium alloy by using, (a) transformer oil, (b) silicon oil and (c) transformer oil + graphite dies coating materials.

The surface morphology of HPDC produced parts has been investigated by scanning electron microscope model JSM-6510LV. The SEM images were taken at 1000x resolution.

The effect of die coating materials like transformer oil, silicon oil, transformer oil + graphite on surface quality of LM9 Aluminium alloy cast parts is shown in Figure 4.7a, 4.7b & 4.7c respectively. Large number of voids and surface irregularities are present on the parts, when dies coated with transformer oil + graphite die coating material as shown in Figure 4.7c. Lesser number of voids and surface irregularities are present on the parts, when dies coated with transformer oil die coating material as shown in Figure 4.7a.

It is clear from figure that surface quality obtained by using transformer oil die coating material is better than silicon oil and transformer oil + graphite die coating material because the molecular weight of transformer oil is higher than silicon oil and transformer oil + graphite. Therefore, surface roughness values decreases with increase in molecular weight.

4.3 Analysis of ADC12 Aluminium Alloy

The experimental data collected as per BBD was used.

4.3.1 Result of Density

Density of casting was measured by using the weighing machine to measure the weight of casting and micrometer to measure the volume of casting.

$$Density\ is\ given\ by\ \rho = weight\ of\ casting \div volume\ of\ casting \tag{4.5}$$

The equation developed for response density is given below:

$$\boldsymbol{Mean\ Density} = -5.91953 + 0.07439 \times \mathrm{A} - 0.16849 \times \mathrm{B} - 0.76848 \times \mathrm{C} + 0.25846 \times \mathrm{D} - 0.00008 \times \mathrm{A} \times \mathrm{A} + 0.00006 \times \mathrm{B} \times \mathrm{B} - 0.00044 \times \mathrm{C} \times \mathrm{C} + 0.08158 \times \mathrm{D} \times \mathrm{D} + 0.00019 \times \mathrm{A} \times \mathrm{B} + 0.00103 \times \mathrm{A} \times \mathrm{C} - 0.00062 \times \mathrm{A} \times \mathrm{D} - 0.00002 \times \mathrm{B} \times \mathrm{C} - 0.00018 \times \mathrm{C} \times \mathrm{D} \tag{4.6}$$

Table 4.7: ANOVA table for density

Source	**Sum of square**	**DF**	**Mean Square**	**F Value**	**Prob. >F**	**%age Contribution**	**Status**
Model	0.93	14	.067	32.19	< 0.0001		Significant
A	0.16	1	0.16	75.43	< 0.0001	17.14	Significant
B	0.48	1	0.48	231.5	< 0.0001	51.41	Significant
C	0.066	1	0.066	31.83	< 0.0001	7.069	Significant
D	0.071	1	0.071	34.02	< 0.0001	7.605	Significant
A^2	0.00671	1	0.00671	3.24	0.0936	0.719	Not Significant
B^2	0.021	1	0.021	10.02	0.0069	2.249	Significant
C^2	0.00033	1	0.00033	0.16	0.6946	0.035	Not Significant
D^2	0.043	1	0.043	20.82	0.0004	4.606	Significant
AB	0.055	1	0.055	26.63	0.0001	5.891	Significant
AC	0.027	1	0.027	13.13	0.0028	2.892	Significant
AD	0.00062	1	0.00062	0.3	0.5916	0.066	Not Significant
BC	0.00002	1	0.00002	0.012	0.9141	0.002	Not Significant
BD	0	1	0	0	1.0000	0	Not Significant
CD	0.00022	1	0.00022	0.11	0.7467	0.024	Not Significant
Residual	0.029	14	0.00207				

Lack of Fit	0.026	10	0.00263	3.87	.1021		Not Significant
Pure Error	0.00272	4	0.00068			0.291	
Cor Total	0.96	28					

Significant Factor: A, B, C, D, B^2, D^2, AB, AC

Insignificant factor: A^2, C^2, AD, BC, BD, CD

In this experiment F-value of the model is 32.19. This signifies that model is significant. There is only a 0.01% chance that a Model with this large value could occur due to noise.

If values of "Prob > F" is less than 0.05 , this indicate factors are significant. If this value is greator than 0.05, this indicate factors are not significant. If there are many insignificant factors (not counting those required to support hierarchy), model reduction may improve your model. In this experiment F-value of Lack of Fit is 3.87, this indicate that Lack of Fit is not significant relative to the pure error. There is a 10.21% chance that a "Lack of Fit F-value" this large could occur due to noise.

The "Pred R-Squared value" of 0.8383 is in reasonable agreement with the "Adj R-Squared value" of 0.9397. Signal to noise ratio is measured by "Adeq Precision". A ratio greater than 4 is desirable. In this experiment signal to noise ratio of 25.103 indicate an adequate signal.

Table 4.8: ANOVA parameters

Std. Dev.	0.046	R-Squared	0.9699
Mean	2.56	Adj R-Squared	0.9397
C.V.	1.78	Pred R-Squared	0.8383
PRESS	0.16	Adeq Precision	25.103

Coefficient of Variation (C.V.) Press: predicated residual sum of squares; Std. Dev.: standard deviance.

The effect of pouring temperature of molten metal, injection pressure, die holding time and die coating on density at different process parameter is shown in Figure 4.8a, 4.8b, 4.8c & 4.8d respectively.

Density is mainly affected by injection pressure. When injection pressure increases, cooling rate of liquid phase increases due to the compaction action. This result indicates the decrease in porosity formation.

Density values of ADC12 aluminium alloy increases, when temperature decreases from 800°C to 760°C (Figure 4.8a). Density of ADC12 aluminium alloy increases with increase in injection pressure and die holding time is shown in Figure 4.8b & 4.8c respectively. Density of die cast parts increases with decrease in pouring temperature due to the reduction in gas porosity. In figure 4.8d silicon oil, transformer oil and transformer oil + graphite are represented on the graph horizontal axis as 1, 2 and 3 respectively. If die is coated with the mixture of transformer oil and graphite powder, density of die cast component increases as shown in Figure 4.8d.

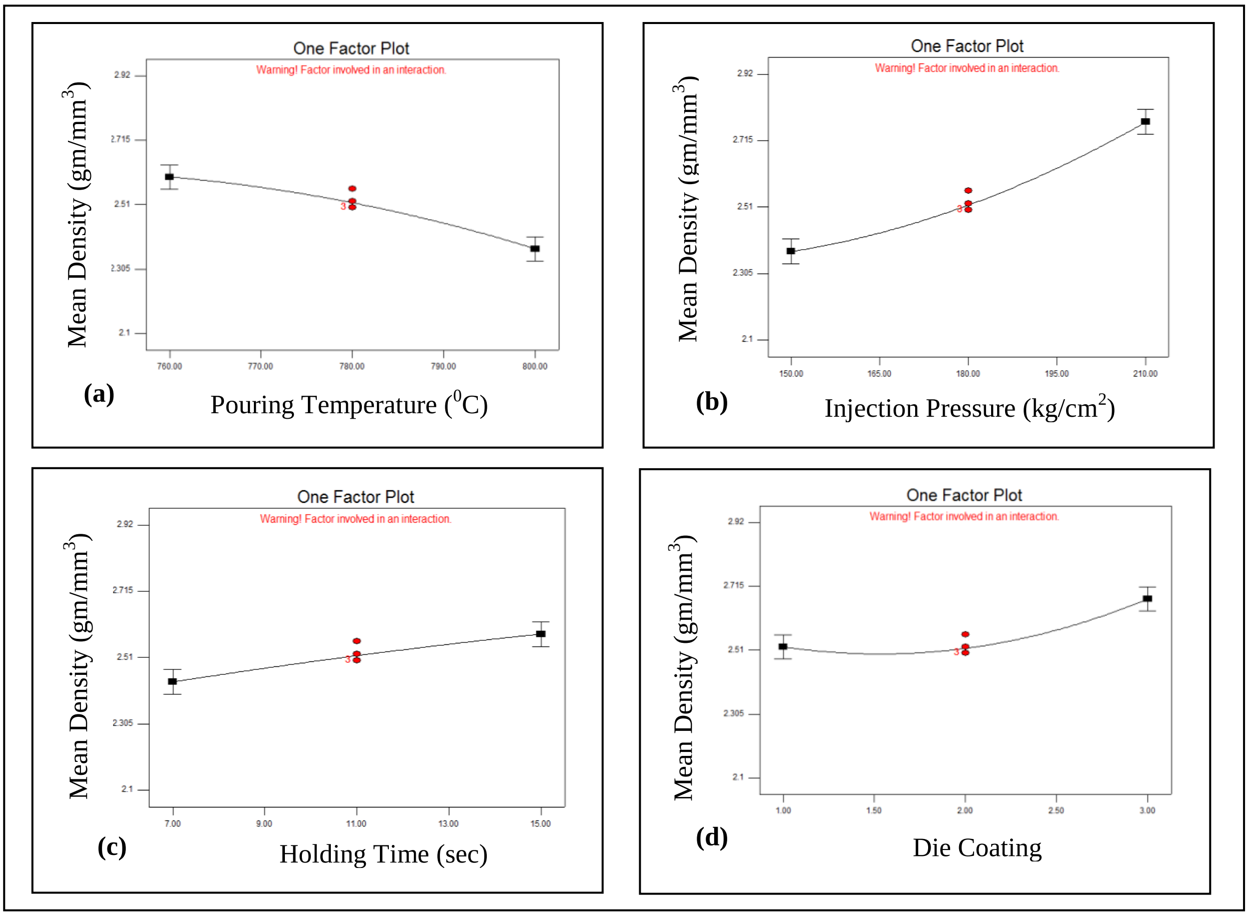

Figure 4.8: Variation of (a) pouring temperature v/s density, (b) injection pressure v/s density, (c) die holding time v/s density and (d) die coating v/s density.

The 3D plots for the effect of pouring temperature and injection pressure, pouring temperature and holding time on density of die cast components is shown in Figure 4.9a & 4.9b respectively.

The density of die cast parts increases with decrease in pouring temperature at particular low pressure and increasing pressure at high pouring temperature. The density of die cast parts increases with decrease in pouring temperature and increase in injection pressure (Figure 4.9a).

The density of die cast parts increases with decrease in pouring temperature at low holding time and increasing holding time at high temperature. The maximum density was obtained at high holding time and lower pouring temperature (Figure 4.9b).

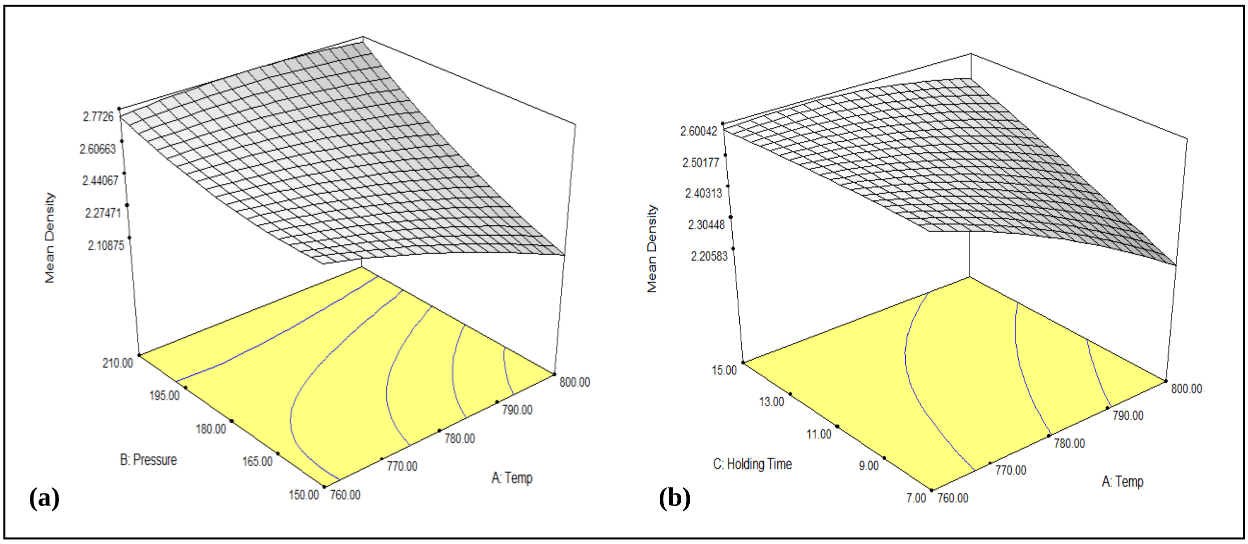

Figure 4.9: 3D plot showing variation of (a) density value with pouring temperature and injection pressure and (b) density value with pouring temperature and die holding time.

4.3.2 Result of Hardness

Hardness of casting was measured on Rockwell hardness tester machine. It is depends upon the indentation diameter on the casting. Pyramid shaped steel ball indenter with minor load of 10 kg on B scale for 10 s was used for measuring the hardness.

The equation developed for response hardness is given below:

$$\boldsymbol{Mean\ Hardness} = -1176.8898 + 2.7192 \times A + 2.0989 \times B + 1.8414 \times C + 26.2687 \times D - 0.0016 \times A \times A - 0.0021 \times B \times B - 0.0641 \times C \times C - 1.4395 \times D \times D - 0.0012 \times A \times B + 0.0025 \times A \times C - 0.0250 \times A \times D - 0.0177 \times B \times C - 0.0333 \times B \times D + 0.5937 \times C \times D \quad (4.7)$$

Table 4.9: ANOVA table for Hardness

Source	Sum of square	DF	Mean Square	F Value	Prob. >F	%age Contribution	Status
Model	236.78	14	16.91	24.07	< 0.0001		Significant
A	37.35	1	37.35	53.14	< 0.0001	14.77	Significant
B	61.34	1	61.34	87.28	< 0.0001	24.25	Significant
C	27.6	1	27.6	39.28	< 0.0001	10.91	Significant
D	28.52	1	28.52	40.58	< 0.0001	11.28	Significant
A^2	2.79	1	2.79	3.97	0.0662	1.103	Not Significant
B^2	24.5	1	24.5	34.86	< 0.0001	9.687	Significant

C^2	6.84	1	6.84	9.74	0.0075	2.705	Significant
D^2	13.44	1	13.44	19.13	0.0006	5.314	Significant
AB	2.3	1	2.3	3.27	0.0923	0.909	Not Significant
AC	0.16	1	0.16	0.23	0.6406	0.063	Not Significant
AD	1	1	1	1.42	0.2528	0.395	Not Significant
BC	18.06	1	18.06	25.7	0.0002	7.141	Significant
BD	4	1	4	5.69	0.0317	1.582	Significant
CD	22.56	1	22.56	32.1	< 0.0001	8.92	Significant
Residual	9.84	14	0.7				
Lack of Fit	7.39	10	0.74	1.21	.4642		Not Significant
Pure Error	2.45	4	0.61			0.969	
Cor Total	246.62	28					

Significant Factor*:* A, B, C, D, B^2, C^2, D^2, BC, BD, CD

Insignificant factor*:* A^2, AB, AC, AD

In this experiment F-value of the model is 24.07. This signifies that model is significant. There is only a 0.01% chance that a model with this large value could occur due to noise.

If values of "Prob > F" is less than 0.05 , this indicate factors are significant. If this value is greator than 0.05, this indicate factors are not significant. If there are many insignificant factors (not counting those required to support hierarchy), model reduction may improve your model.

In this experiment F-value of Lack of Fit is 1.21, this indicate that Lack of Fit is not significant relative to the pure error. There is a 46.42% chance that a "Lack of Fit F-value" this large could occur due to noise.

The "Pred R-Squared value" of 0.8119 is in reasonable agreement with the "Adj R-Squared value" of 0.9209. Signal to noise ratio is measured by "Adeq Precision". A ratio greater than 4 is desirable. In this experiment signal to noise ratio of 19.637 indicate an adequate signal.

Table 4.10: ANOVA parameters

Std. Dev.	0.84	R-Squared	0.9601
Mean	82.84	Adj R-Squared	0.9202
C.V.	1.01	Pred R-Squared	0.8119
PRESS	46.38	Adeq Precision	19.637

Coefficient of Variation (C.V.) Press: predicated residual sum of squares; Std. Dev.: standard deviance.

The effect of pouring temperature of molten metal, injection pressure, die holding time and die coating on hardness at different process parameter is shown in Figure 4.10a, 4.10b, 4.10c & 4.10d respectively.

Holding time is the outstanding parameter that affects the hardness of die cast parts. Hardness value of ADC12 aluminium alloy increases with decrease in pouring temperature of molten metal (Figure 4.10a). Hardness of ADC12 aluminium alloy increases with increase in injection pressure and die holding time as shown in Figure 4.10b & 4.10c respectively. In figure 4.10d silicon oil, transformer oil and transformer oil + graphite are represented on the graph horizontal axis as 1, 2 and 3 respectively. If die is coated with transformer oil in place of silicon oil, hardness of die cast component increases (Figure 4.10d). Due to increase in cooling rate hardness of die cast parts increases with increase in injection pressure.

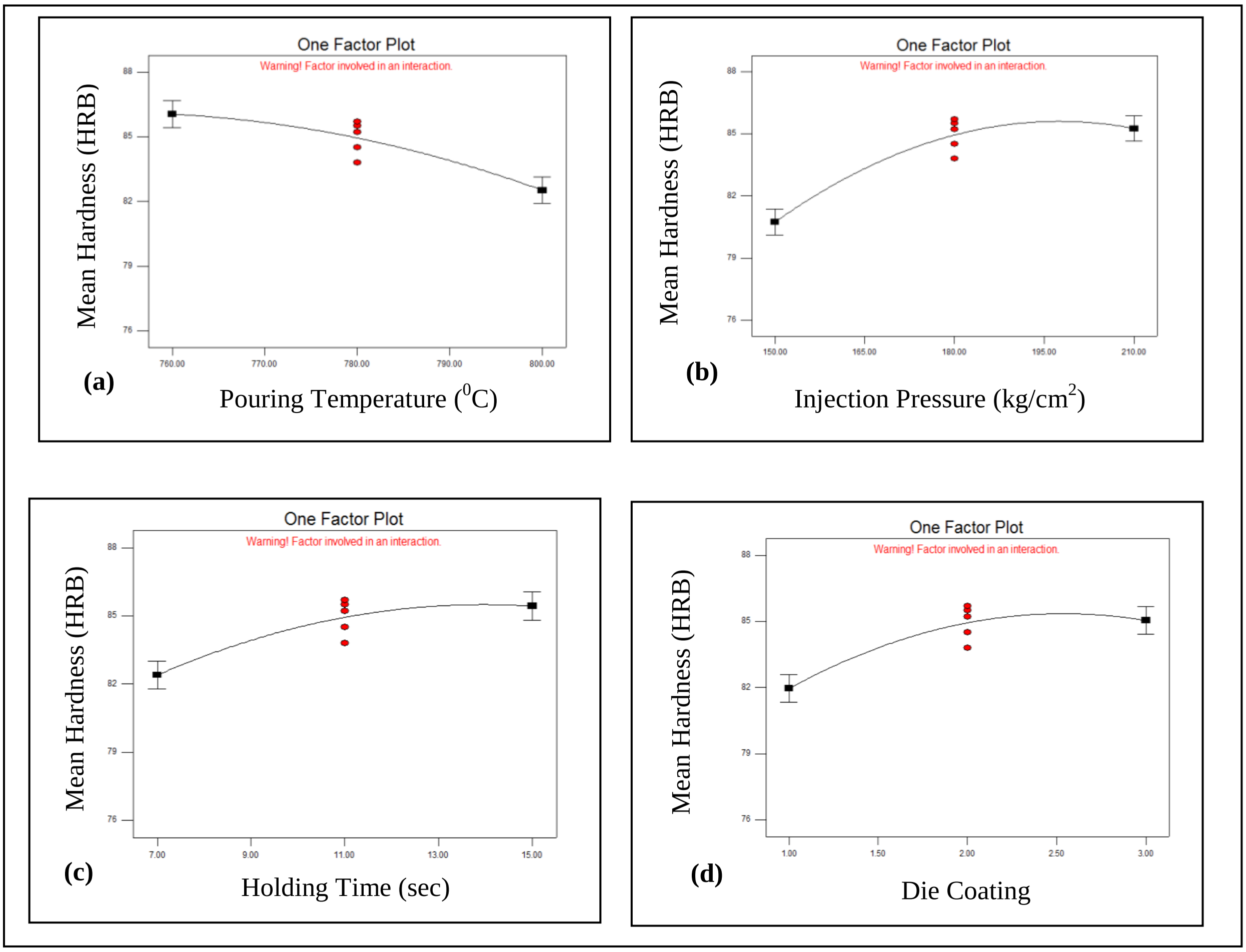

Figure 4.10: Variation of (a) pouring temperature v/s hardness, (b) injection pressure v/s hardness, (c) die holding time v/s hardness and (d) die coating v/s hardness.

The 3D plots for the effect of injection pressure and holding time, injection pressure and die coating, holding time and die coating on hardness of die cast components is shown in Figure 4.11a, 4.11b & 4.11c respectively.

In figure 4.11a and 4.11c silicon oil, transformer oil and transformer oil + graphite are represented on the graph as 1, 2 and 3 respectively. Increasing injection pressure with lower value of holding time and increasing the injection pressure with silicon oil was used for coating of dies, hardness of die cast components increases as shown in figure 4.11a & 4.11b respectively. It is minimum at lower value of injection pressure and holding time. Hardness value of casting increases with increase in holding time as transformer oil + graphite was used for coating of dies (Figure 4.11c).

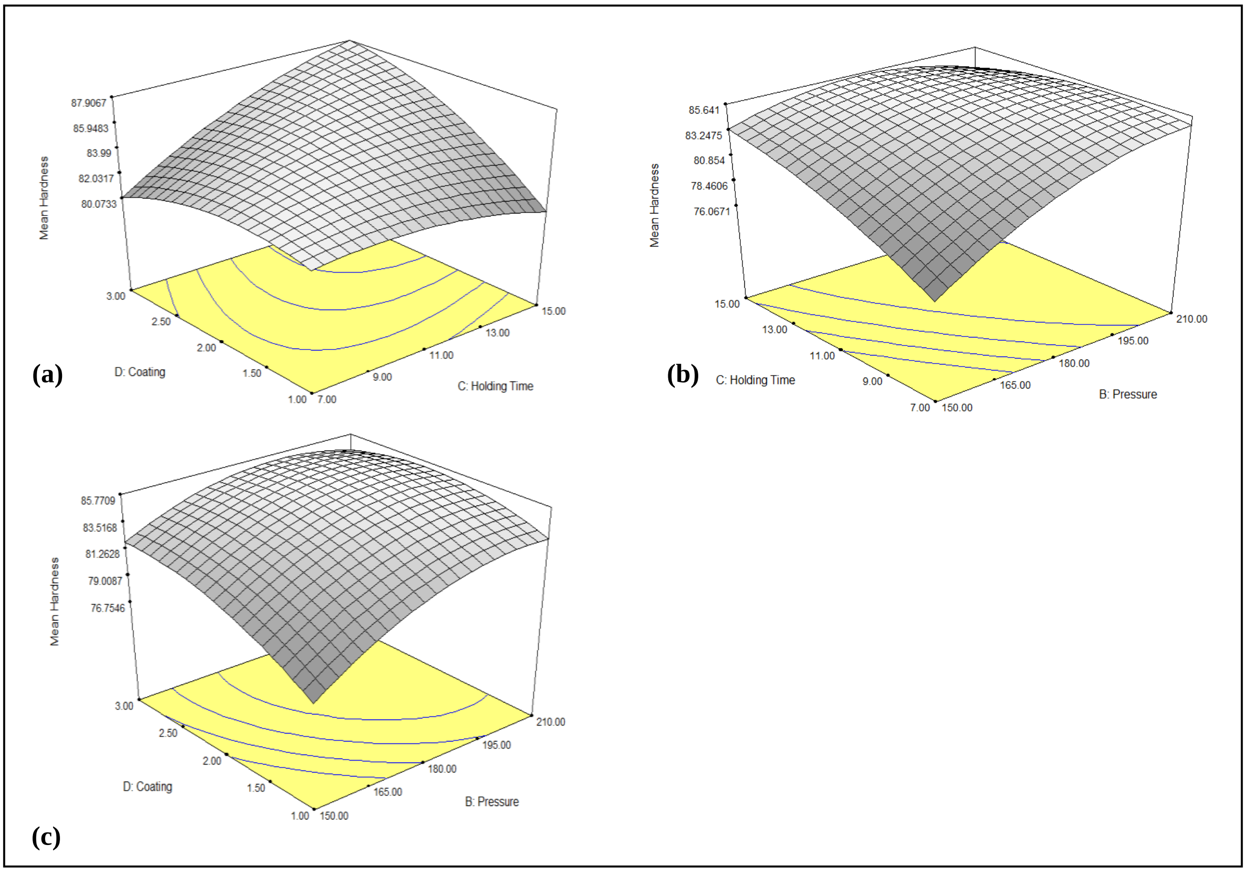

Figure 4.11: 3D plot showing variation of (a) hardness value with die holding time and die coating, (b) hardness value with injection pressure and die holding time and (c) hardness value with injection pressure and die coating.

4.3.3 Result of Surface Roughness

Mitutoyo model SJ-400 tester was used for measurement of surface roughness. The tester uses a stylus method of measurement. Tester has a profile resolution of 12nm and surface roughness can be measure upto 100µm. In this experiment tracing length of 4.8 mm was used.

The equation developed for response surface roughness is given below:

$$\begin{aligned} \textit{Mean Surface Roughness} &= -188.35421 + 0.48002 \times A - 0.09759 \times B + 1.20988 \times C + 2.94812 \\ &\times D - 0.0002 \times A \times A + 0.00008 \times B \times B + 0.00744 \times C \times C + 0.31674 \\ &\times D \times D + 0.00005 \times A \times B - 0.00189 \times A \times C - 0.00765 \times A \times D \\ &- 0.00027 \times B \times C + 0.00775 \times B \times D + 0.05625 \times C \times D \end{aligned} \quad (4.8)$$

Table 4.11: ANOVA for Surface Roughness

Source	Sum of square	DF	Mean Square	F Value	Prob. >F	%age Contribution	Status
Model	4.28	14	0.31	108.98	< 0.0001		Significant
A	0.15	1	0.15	52.98	< 0.0001	3.54	Significant
B	1.44	1	1.44	511.94	< 0.0001	34	Significant
C	0.34	1	0.34	121.65	< 0.0001	8.02	Significant
D	0.82	1	0.82	293.45	< 0.0001	19.3	Significant
A^2	0.086	1	0.086	30.54	< 0.0001	2.03	Significant
B^2	0.04	1	0.04	14.16	0.0021	0.94	Significant
C^2	0.092	1	0.092	32.83	< 0.0001	2.17	Significant
D^2	0.65	1	0.65	232.13	< 0.0001	15.3	Significant
AB	0.00423	1	0.00422	1.51	0.2398	0.1	Not Significant
AC	0.092	1	0.092	32.86	< 0.0001	2.17	Significant
AD	0.094	1	0.094	33.4	< 0.0001	2.22	Significant
BC	0.00423	1	0.00423	1.51	0.2398	0.1	Not Significant
BD	0.22	1	0.22	77.13	< 0.0001	5.19	Significant
CD	0.2	1	0.2	72.23	< 0.0001	4.72	Significant
Residual	0.039	14	0.0028				
Lack of Fit	0.033	10	0.00325	1.94	.2733		Not Significant
Pure Error	0.00671	4	0.00168			0.16	
Cor Total	4.32	28					

***Significant Factor**:* A, B, C, D, A^2, B^2, C^2, D^2, AC, BD, CD

***Insignificant factor**:* AB, BC

In this experiment F-value of the model is 108.89. This signifies that model is significant. There is only a 0.01% chance that a Model with this large value could occur due to noise.

If values of "Prob > F" is less than 0.05 , this indicate factors are significant. If this value is greator than 0.05, this indicate factors are not significant. If there are many insignificant factors (not counting those required to support hierarchy), model reduction may improve your model. In this experiment F-value of Lack of Fit is 1.94, this indicate that Lack of Fit is not significant relative to the pure error. There is a 27.33% chance that a "Lack of Fit F-value" this large could occur due to noise.

The "Pred R-Squared value" of 0.9141 is in reasonable agreement with the "Adj R-Squared value" of 0.9418. Signal to noise ratio is measured by "Adeq Precision". A ratio greater than 4 is desirable. In this experiment signal to noise ratio of 34.044 indicate an adequate signal.

Table 4.12: ANOVA parameters

Std. Dev.	0.053	R-Squared	0.9709
Mean	1	Adj R-Squared	0.9418
C.V.	5.29	Pred R-Squared	0.9141
PRESS	0.2	Adeq Precision	34.044

Coefficient of Variation (C.V.) Press: predicated residual sum of squares; Std. Dev.: standard deviance.

Pouring temperature of molten metal, injection pressure, die holding time and die coating are the significant factors which influence the surface roughness of die cast components as shown in Figure 4.12.

Surface roughness of die cast components is mainly affected by the injection pressure. It was observed that surface roughness value of ADC12 aluminium alloy decreases with decrease in pouring temperature (Figure 4.12a). Surface roughness values increases with decrease in injection pressure and holding time is shown in Figure 4.12b & 4.12c respectively. In figure 4.12d silicon oil, transformer oil and transformer oil + graphite are represented on the graph horizontal axis as 1, 2 and 3 respectively. If die is coated with a mixture of transformer oil and graphite, surface roughness of die cast component increases (Figure 4.12d).

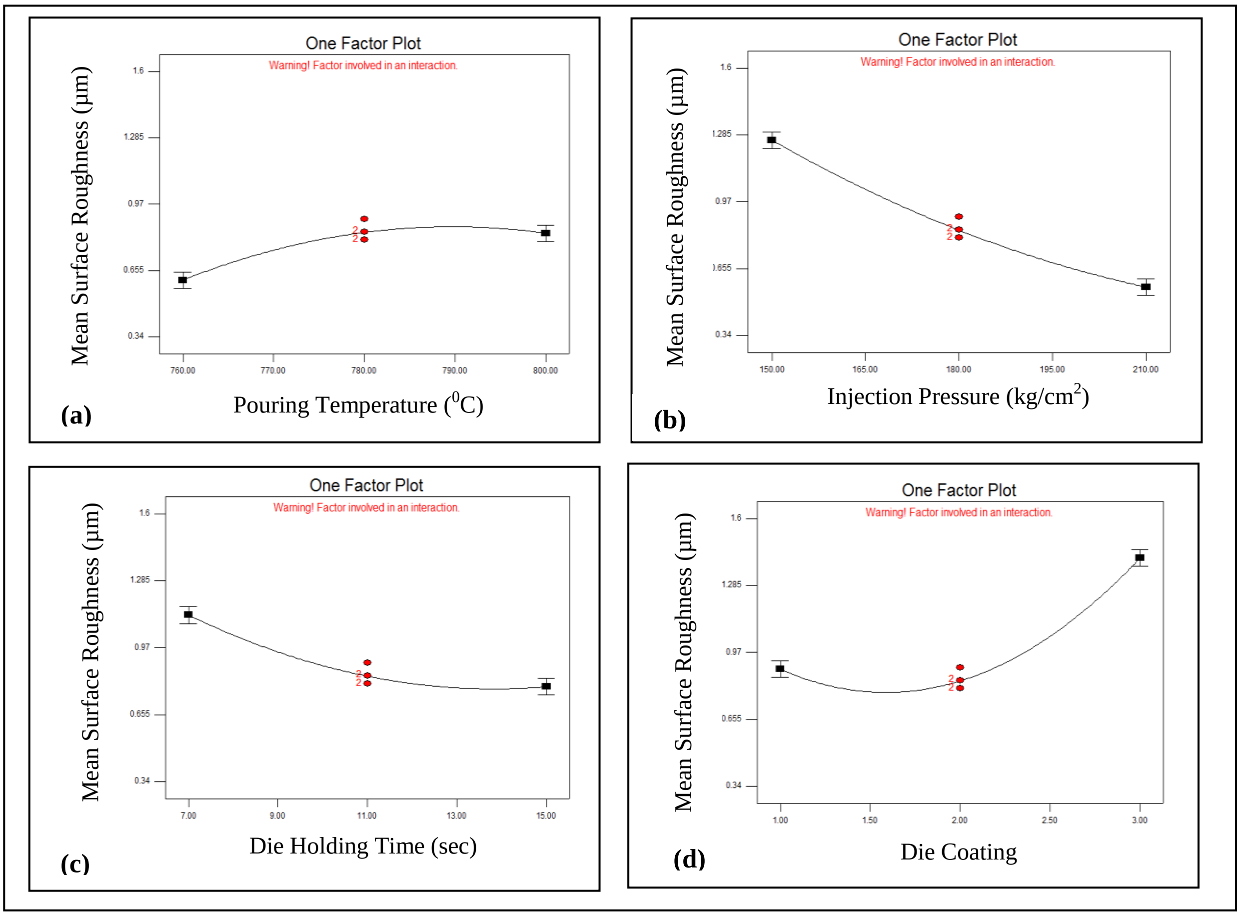

Figure 4.12: Variation of (a) pouring temperature v/s surface roughness, (b) injection pressure v/s surface roughness, (c) die holding time v/s surface roughness and (d) die coating v/s surface roughness.

The 3D plots for the effect of pouring temperature and die holding time, pouring temperature and die coating, injection pressure and die coating, die holding time and die coating on surface roughness of die cast components is shown in Figure 4.13a, 4.13b, 4.13c & 4.13d respectively.

The surface roughness of die cast components decreases with increase in holding time at high pouring temperature. It was minimum at high holding time and high pouring temperature as shown in Figure 4.13a.

In figure 4.13b, 4.13c and 4.13d silicon oil, transformer oil and transformer oil + graphite are represented on the graph as 1, 2 and 3 respectively. If the die is coated with transformer oil and low pouring temperature was used, surface roughness was found to be minimum (Figure 4.13b).

The surface roughness of die cast parts decreases with increase in injection pressure with desired die coating material and surface roughness was found to be minimum at high injection pressure with silicon oil was used as die coating material (Figure 4.13c).

The surface roughness of die cast parts decrease with increase in holding time with desired die coating material and surface roughness was found to be minimum at high holding time with silicon oil was used as die coating material (Figure 4.13d).

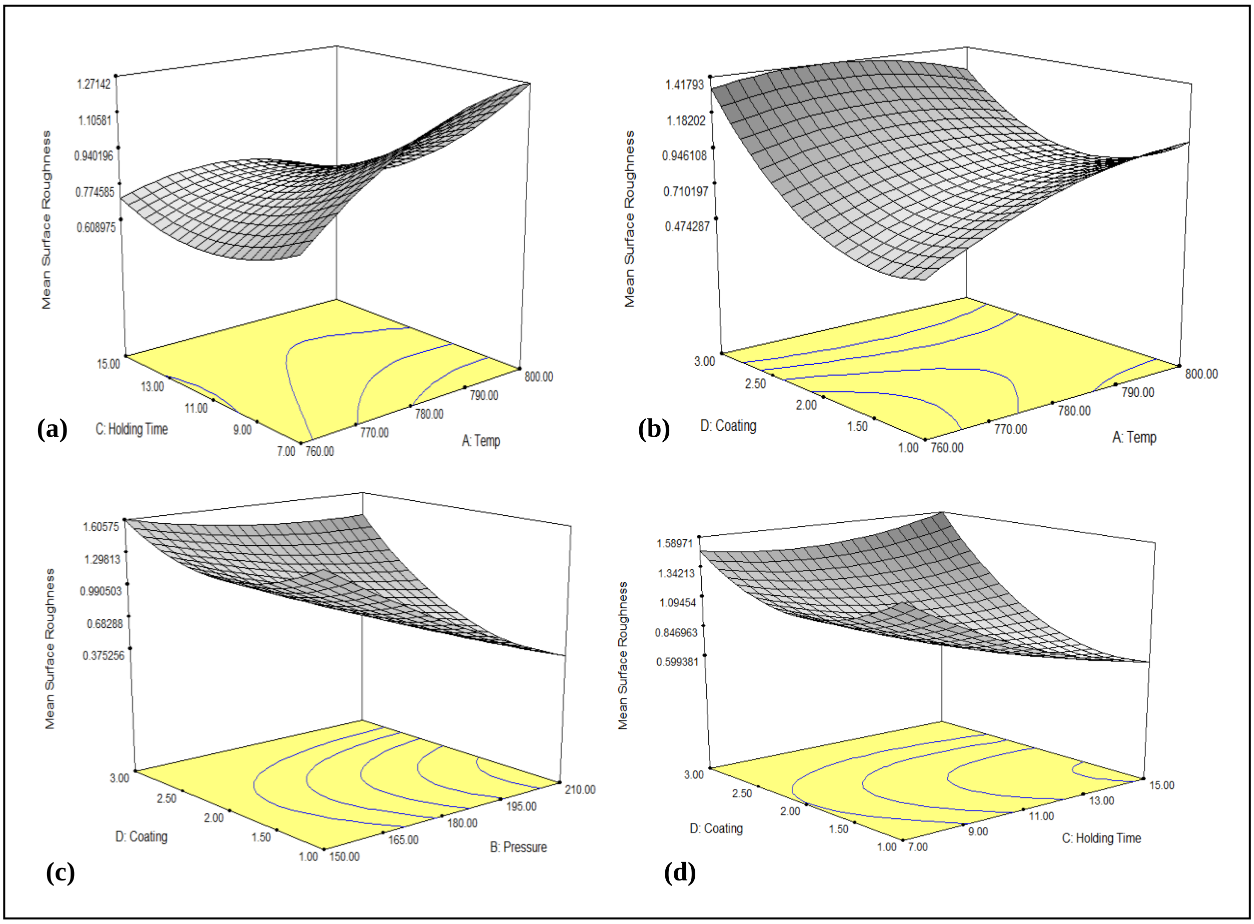

Figure 4.13: 3D plot showing variation of (a) surface roughness value with pouring temperature and die holding time, (b) surface roughness value with pouring temperature and die coating, (c) surface roughness value with injection pressure and die coating and (d) surface roughness value with die holding time and die coating.

4.3.4 SEM Study of Surface Quality

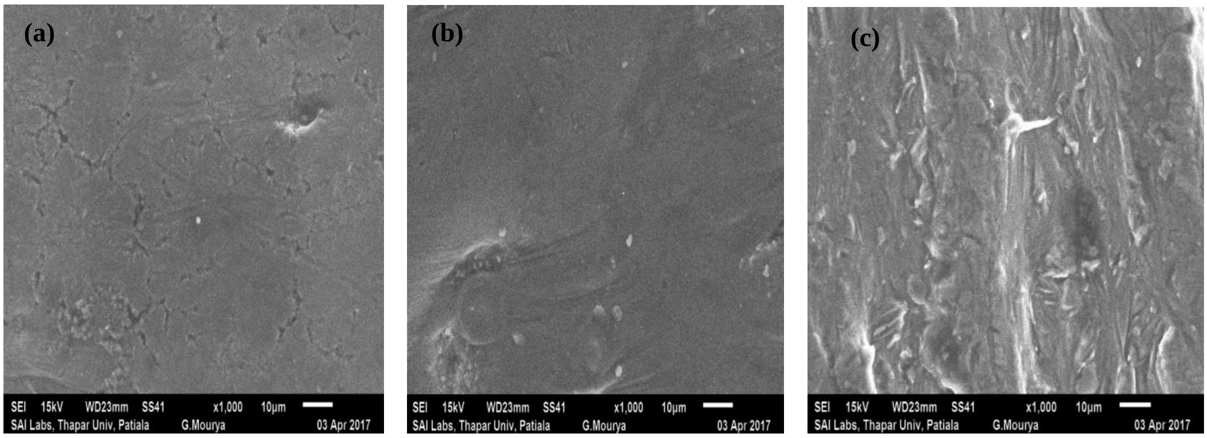

Figure 4.14: Surface quality obtained through HPDC of ADC12 Aluminium Alloy by using, (a) transformer oil, (b) silicon oil and (c) transformer oil + graphite dies coating materials.

The surface morphology of HPDC produced parts has been investigated by scanning electron microscope model JSM-6510LV. The SEM images were taken at 1000x resolution.

The effect of die coating materials like transformer oil, silicon oil, transformer oil + graphite on surface quality of ADC12 aluminium alloy die cast parts are shown in Figure 4.14a, 4.14b & 4.14c respectively. Large number of voids and surface irregularities are present on the parts, when dies coated with transformer oil + graphite die coating material as shown in Figure 4.14c. Lesser number of voids and surface irregularities are present on the parts, when dies coated with transformer oil die coating material as shown in Figure 4.14a.

It is clear from figure that surface quality obtained by using transformer oil die coating material is better than silicon oil and transformer oil + graphite die coating materials because the molecular weight of transformer oil is higher than silicon oil and transformer oil + graphite. Therefore, surface roughness values decreases with increase in molecular weight.

Chapter 5

Conclusions

- High pressure die casting can produce parts similar to the final product. HPDC is cost-effective because parts produced are accurate in dimension with narrow tolerance. HPDC processes are highly productive and offer high repeatability.
- Injection pressure is the main factor which affects the density of LM9 and ADC12 aluminium alloy produced parts.
- Die coating materials have less effect on density.
- Density of die cast products increases with decrease in pouring temperature and increases with injection pressure and die holding time of both LM9 and ADC12 aluminium alloys.
- Die holding time has been found as a prominent parameter that affects the hardness of the parts, manufactured from LM9 aluminium alloys whereas hardness of ADC12 aluminium alloy produced parts were highly affected by injection pressure.
- Increasing injection pressure and die holding time, hardness of both LM9 and ADC12 aluminium alloy parts increases.
- Maximum hardness value is obtained at 780^0C pouring temperature in both LM9 and ADC12 aluminium alloy produced parts.
- Injection pressure is the outstanding parameter that influence the surface roughness of LM9 and ADC12 aluminium alloy die cast parts whereas pouring temperature of molten metal has less influence on surface roughness.
- Increase in die holding time and injection pressure, surface roughness of both LM9 and ADC12 aluminium alloys die cast component decrease.
- Surface roughness of LM9 and ADC12 aluminium alloy die cast components decrease with decrease in pouring temperature.
- Surface quality obtained through HPDC by using transformer oil as die coating materials is better than silicon oil and transformer oil + graphite.

References

1. Shouxun Ji, Feng Yan, Zhongyun Fan, Development of a High strength Al–Mg2Si–Mg–Zn Based Alloy for High Pressure Die Casting, Materials science & Engineering A 626 (2015)165–174.
2. Magnesium Die Casting Handbook, NADCA, 1998, ISBN-13: 9780750642866.
3. John E. Hatch., Aluminum: Properties and Physical Metallurgy. American Society of Metals, Metals Park, Ohio, 1984.
4. Introduction to Die Casting; NADCA Publication: 101BK, © 2007 by North American Die Casting Association, Arlington Heights, Illinois.
5. North American Die Casting Association, 241holbrook Drive, Wheeling, IL 60090 (2009).
6. http://www.die casting.org/die casting process/2017/03/28/.
7. K. Domkin, J.H. Hattel, J. Thorborg, Investigates Soldering of Cast Alloys to the Dies Continuing Source of Die Surface Damage in the Aluminium Die Casting, Journal of Materials Processing Technology 209 (2008) 4051–4061.
8. http://diecasting.com/blog/2016/03/23/hot-chamber-vs-cold-chamber-die-casting/.
9. ASM Handbook Casting 15, (2008) ISBN: 978-0-87170-711-6.
10. Copyright © 2009 eFunda, Inc.
11. DYCOTE Manuals of Feseco GmbH, Germany, www.vesuvius.com/en/our-solutions/en-au/foundry/non-ferrous-foundry/die-dressings-and-coatings.html/2017/03/28/.
12. Hanano, United States Patent. Aug. 13, 1991, Patent Number: 5,039,435.
13. Matthew S. Dargusch, G. Dour, N. Schauer, C.M. Dinnis, G. Savage, The Influence of Pressure During Solidification of High Pressure Die Cast Aluminium Telecommunications Components, Journal of Materials Processing Technology 180.1 (2006) 37-43.
14. Maleki, A., B. Niroumand, A. Shafyei, Effects of Squeeze Casting Parameters on Density, Macrostructure and Hardness Of LM13 Alloy, Materials Science and Engineering A 428.1 (2006) 135-140.
15. Abtan, Najeeb S., Kadhim H. Ghlaim, Comparision of Applied Pressure Effect on Improving Density, Hardness, And Microstructure By Both Squeeze Casting Process

and Pressure Die Casting Process For 380-Al Alloy, The Iraqi Journal For Mechanical and Material Engineering 12.2 (2012) 334-343.

16. G.O. Verrana, R.P.K. Mendes, L.V.O. Dalla Valentina, DOE Applied to Optimization of Aluminum Alloy Die Castings, Journal of Materials Processing Technology 200 (2008) 120–125.
17. Wang, Yucong, A Study of PVD Coatings and Die Materials for Extended Die-Casting Die Life, Surface and Coatings Technology 94 (1997) 60-63.
18. C. Mitterer A, F. Holler, F. Ustel, D. Heim, Application of Hard Coatings in Aluminium Die Casting—Soldering, Erosion and Thermal Fatigue Behaviour, Surface and Coatings Technology 125.1 (2000) 233-239.
19. O. Salas, K. Kearns, S. Carrera, J.J. Moore, Tribological Behavior of Candidate Coatings For Al Die Casting Dies, Surface and Coatings Technology 172.2 (2003) 117-127.
20. Hajjari, E., and M. Divandari, An Investigation on the Microstructure and Tensile Properties of Direct Squeeze Cast And Gravity Die Cast 2024 Wrought Al Alloy, Materials & Design 29.9 (2008) 1685-1689.
21. Obiekea, K., S. Y. Aku, and D. S. Yawas, Influence of Pressure on the Mechanical Properties and Grain Refinement of Die Cast Aluminium A1350 Alloy, Advances In Applied Science Research 3(6) (2012) 3663-3673.
22. Zhang, Yijie, Naiheng Ma, and Haowei Wang, Improvement of Yield Strength of LM24 Alloy, Materials & Design 54 (2014) 14-17.
23. Lifang Hu, Shaoping Chen, Yang Miao, Qingsen Meng, Die-Casting Effect on Surface Characteristics of Thin-Walled AZ91D Magnesium Components, Applied Surface Science 261 (2012) 851-856.
24. Syrcos, G. P, Die Casting Process Optimization Using Taguchi Methods, Journal of Materials Processing Technology 135.1 (2003) 68-74.
25. Penghuai Fu, Alan A. Luo, Haiyan Jiang, Liming Peng, Yandong Yu, Chunquan Zhai, Anil K. Sachdev, Low-Pressure Die Casting of Magnesium Alloy AM50: Response to Process Parameters, Journal of Materials Processing Technology 205.1 (2008) 224-234.
26. Lalit Kumar, Anirban Bhattacharya, Ajay Batish, Multi-Response Optimization of Process Parameters In Cold Chamber Pressure Die Casting, M. Tech. Thesis, Thapar University, Patiala, 2010, http://dspace.thapar.edu: 8080/jspui/bitstream/10266/1292/3/ 1292.pdf.

27. Zuqi Hu., Injection Parameters Optimization and Artificial Aging of Automotive Die Cast Aluminum Alloy, Materials and Manufacturing Processes (2015) DOI: 10.1080/10426914.2015.1004706.
28. Jayant K. Kittur, G. C. Manju nath Patel and Mahesh B. Parappagoudar, Modeling of Pressure Die Casting Process: An Artificial Intelligence Approach, International Journal of Metal Casting (2015) DOI: 10.1007/S40962-015-0001-7.
29. Dasaratha Prabhu, and Ramesh Babu, Investigating the significance of parameters affecting the defects in HPDC component using design of experiment method, IOSR Journal of Environmental Science, Toxicology and Food Technology 4 (2013) 04-09.
30. Nahed A. El-Mahallawy , Mohamed A. Taha, Engenius Pokora, Friedrich Klein, On the influence of process variables on the thermal conditions and properties of high pressure die-cast magnesium alloys, Journal of Materials Processing Technology 73.1 (1998) 125-138.
31. Zhi-Peng Guo, Shou-Mei Xiong, Bai-Cheng Liu, Mei Li, and John Allison, Effect of Process Parameters, Casting Thickness, and Alloys on the Interfacial Heat-Transfer Coefficient in the High-Pressure Die-Casting Process, Metallurgical and Materials Transactions A 39a (2008) 2896-2905.
32. X. Li, S.M. Xiong, Z. Guo, Improved Mechanical Properties in Vacuum-Assist High-Pressure Die Casting of AZ91D Alloy, Journal Of Materials Processing Technology 231 (2016) 1–7.
33. S.G. Lee, A.M. Gokhale, G.R. Patel, M. Evans, Effect of Process Parameters on Porosity Distributions in High-Pressure Die-Cast AM50 Mg-Alloy, Materials Science and Engineering A 427.1 (2006) 99-111.
34. H.D. Zhao, F. Wang, Y.Y. Li,W. Xi., Experimental And Numerical Analysis of Gas Entrapment Defects In Plate ADC12 Die Castings, Journal of Materials Processing Technology 209.9 (2008) 4537-4542.
35. S. Farahany, A. Ourdjini, M.H. Idrsi, S.G. Shabestari, Evaluation of the Effect of Bi, Sb, Sr and Cooling Condition on Eutectic Phases In An Al–Si–Cu Alloy (ADC12) By In Situ Thermal Analysis, Thermo Chemical Acta 559 (2013) 59-68.
36. He Zhen, Zhang Xu-Tao, Xie Gui-Qing, Product Quality Improvement Through Response Surface Methodology : A Case Study, Proceedings International Conference On Technology Innovation And Industrial Management, Phuket, Thailand (2013) S4-120 -130.