FORMULATE METAL-BINDER MIXTURE FOR ROOM TEMPERATURE CASTING

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Mechanical Engineering with Honours

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"FORMULATE METAL-BINDER MIXTURE FOR ROOM TEMPERATURE CASTING"** was prepared by **WONG SHI KAR** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Mechanical Engineering with Honours at Universiti Tunku Abdul Rahman.

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ABSTRACT

Addressing persistent challenges in the foundry industry, such as energy consumption and air pollution, this project explores room-temperature metal casting. This innovative project suspends metal powder in a binder solution to form a castable form, eliminating the need for traditional foundries. The procesx is followed by the therimal treatment, including debinding and sintering, to produce the final article. The objectives of this projects including figure out the optimized independent variables, and study the mechanical properties and rheological behaviour of the slurry. Reusable silicone or 3D printed resin molds significantly cut mold production time and metal melting enrgy use. The experiment procedure, including mixing metal powder with binder, homogenizing the mixture, pouring it into silicone molds, conducting tests, curing the cast product, and finally analyzing the samples' internal structures using a scanning electron microscope (SEM). The Taguchi Method optimizes the metal mix to reduce defects, with tests on mechanical properties like density, hardness, and rheology confirming the ink's quality. In conclusion, the optimize formulation of 60 wt% of 17-4PH metal, 1.5 wt% of binder and 6 wt% of plasticizer show a non-newtonian flowable slurry mixture and casted in silicone mould. In which the green article formed has the insignificant porosity and good surface finishing. The article is then process under debind temperature of 210 deg and vavuum sintered of 1350 deg to form a final article which has a density > 90% and average hardness of 207 HV. This has demonstrated that this method present a more suitable rapid casting solution compared to traditional sand casting method.

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LIST OF SYMBOLS / ABBREVIATIONS

τ	shear stress, Pa
$\dot{\gamma}$	shear strain rate, s^{-1}
k	consitency of the fluid, Pas^{n}
n	flow index, dimensionless
η	viscosity, $Pa\ s^{-1}$
D	diffusion coefficient, m^{2}/s
φ	concentration, mol/m^{3}
t	time, s
x	position, m

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Nowadays, the casting process has a significant role in the manufacturing process which consistently produces high-accuracy metal components. According to New Research Insight Report 2023, the demand of metal casting is expected to rise steadily between 2023 and 2030. The growth rate of metal casting industry is estimated to be CAGR of 6% by processes of sand casting, investment casting (Research Nester 2022). Malaysia is also one of the regions listed that will increase the market of metal casting due to the development of automotive, building and construction, electronics.

For the conventional casting technique such as sand casting, the temperature to melt steel into molten metal is around $1593 - 1704℃$ (Inductotherm Corp. 2015) . To melt metal, it required electricity and natural gas, as well as labour and facing storage, and logistic issues. According to the Malaysian Iron and Steel Industry Federation (MISIF), the energy cost in the steel industry is estimated to be more than RM 1.5 billion this year (DTUKENMEZ 2022) . In fact, when melting the metal, carbon dioxide is emitted from the process of melting metal, which lead to greenhouse gas emission (GHG) (Tharumarajah et al. 2009). As the world temperature increase and the greenhouse gas emission present cause challenges in steel industry. Therefore, the demand for a new casting technique that can fulfill low-carbon fuels, reducing energy demand and improving energy efficiency increases drastically (Carabalí et al. 2018) .

Therefore, it can be concluded that the potential of the room temperature casting is huge and impactful. The main reason is the casting technique in this project does not involve any heating process at the initial stage. The metal powder is mixed with binder and other components and then the mixture is poured into the molds and letting it to cure at room temperature. Only the sintering process involves the heating process which is unavoidable.

This project explores the use of metal-binder mixtures for room-temperature casting, offering a practical alternative to methods like silicone or

3D printing. This approach allows for precise and durable component production without initial metal heating, making it ideal for complex geometries. Compatibility with silicone molds, which are cost-effective, non-toxic, chemically resistant, and reusable, further enhances its appeal. The project's primary aim is to determine the optimal metal-binder mixture proportions by considering factors such as additives, composition, and casting techniques. Achieving consistent die-filling and uniformity is crucial. Challenges include addressing surface porosity and ensuring a homogeneous blend of metal and additives. Success in this endeavor promises to elevate room-temperature metal-binder casting to new levels of precision, cost-effectiveness, and design flexibility (Hambali Boejang 2009).

1.2 Importance of the Study

The formulation of a metal-binder mixture for room-temperature casting has significant potential in the modern manufacturing process. Room temperature casting is more cost-effective and energy conservation than the traditional manufacturing process. This is due to heat demand is not needed at the mixing and curing stage, but still needed at post processing, thus it saves energy and manpower which lead to cost saving. Besides, it also promotes sustainable and environment-friendly casting way which is in line with the Sustainable Development Goal (SDG).

Moreover, its ability to cast without subjecting metals to extreme temperatures opens new horizons in cost saving. Molds that are used to cast metal at room temperature save lots of money. This is due to the company doesn’t need to use the metal mold set or sand mold to perform the casting process, whereas a cheaper mold can be utilized such as silicone mold. Silicone molds can be reused and it is easy to create and be found on the market. This also allows the metal-binder casting to have high flexibility in complex geometries.

Besides, the porosity-free metal-binder mixture can have widely application in many fields such as aerospace, automotive and so on which requires high accuracy without hurting the properties of the metal.

In conclusion, this study is significant for its potential to revolutionize traditional casting techniques in the industry, offering new opportunities for innovation and expanding applications in manufacturing processes.

1.3 Problem Statement

By referring to the casting technologies available in the market, it can be known that the common problems found in the casting process as well as the problems this project will face.

The quality of cast products produced through sand casting often suffers from shrinkage, distortion, porosity, and poor mechanical properties such as low strength (Blair et al. 2005b; Niklas et al. 2015; Timelli and Fabrizi 2014; Venkatesan and Xavior 2018). For the dry sand casting, is expensive and time-consuming due to a mold has to be thrown after casting. Investment casting also occurs porosity, while plaster mould casting might occur gas porosity problems due to the low permeability of the plaster mould. However, plaster mold casting can only apply on the low melting temperature metals such as aluminium, and coppers (K.G. Swift and J. BookerD. 2013) .

Taking sand casting as example, the reason for the occurrence of air bubbles in the metal casting internally and at the surface is due to during solvent evaporation, the gas is trapped in the metal, and due to different dry rates and permeability of the surface, the air cannot escape from the metal’s interior (Xu et al. 2022). Besides, shrinkage and cold shut are also a big problem in the casting process. This issue arises because the density of the molten phase is lower than that of the solid phase, resulting in imperfections on both the surface and within the cast product. Ultimately, these imperfections weaken the cast product. (Vaibhav Ingle and Madhukar Sorte 2017a) . Moreover, for conventional casting modern occurs also cracks or tears due to possible reasons, namely shrinkage within the die or thermal imbalance in the die. However, it would not occur in this project due to this casting process involves melting metal.

The reason of these problems need to be solved is due to those defects highly affect the mechanical properties of the cast product. For instance, the porosity at the internal of the cast product causes a weak point that is not able to withstand high stress. Eventually, it is not able to perform what the metal part requires.

To achieve this goal, quantitative methods will be employed, such as measuring the rheology of the mixture. Different concentrations of the binder mixture will be compared to determine the most suitable combination, which will help improve the casting process and reduce porosity-related issues. By allowing for a slower curing rate, gases will have enough time to escape before the metal solidifies, leading to higher-quality castings.

In conclusion, this research aims to enhance the casting process by minimizing porosity through improved binder mixture formulations and optimizing curing rates. This will result in superior mechanical properties and overall performance of the final cast products.

1.4 Aim and Objectives

There are three main objectives that have to be achieved upon completion of this project.

1) To maximize the ratio of independent variables (Acetone, Plasticizer, Deionized Water) with the aim of achieving 80% density in green part.
2) To study the mechanical properties of the final cast products.
3) To investigate rheological behaviour of the slurry.

1.5 Scope and Limitation of the Study

The scope of the study revolves around the properties of the metal-binder mixture. It involves the study of non-Newtonian fluids and rheology which will highly affect the context of the metal-binder.

As for the limitation of the study, the solvent to formulate a metal binder mixture will be Acetone, Deionized Water (DI Water) and Plasticiser. The formulation of the metal binder mixture has to be based on three of these solvents. The ratio of these solvents in the metal-binder mixture will highly affect the final casting product.

Another important limitation is the scope of silicone mold. The scope of this study only involves silicone mold when casting the metal binder mixture. This will affect the surface of the final product which relates to the main objectives of this project.

1.6 Contribution of the Study

Metal casting has been associated with high temperatures, molten metals, and moulds. To produce parts, traditional casting method requiring big factories, huge manpower, and high energy consumption, high operating cost, and not environmental friendly.

The significant impact of this advanced technology is its ability to facilitate small-scale manufacturing and produce complex designs such as chess pieces, which are impossible to achieve using traditional casting methods. Additionally, it opens up possibilities for casting other metals such as copper and aluminium at room temperature. Moreover, this technology requires only a small setup, short lead time and does not require a large workforce compared to traditional casting methods. By lowering the barriers to entry, this technique empowers small-scale manufacturers, entrepreneurs, and even hobbyists to bring their ideas to life, greatly reducing costs. Whether it's creating custom components for a project or producing small batches of niche products, room temperature casting offers a sustainable technology.

1.7 Outline of the Report

An overview of the project, including background data and an explanation of its goals, purpose, scope, and problem it addresses, is given in Chapter One of the report. A thorough assessment of the literature is done in Chapter 2, with an emphasis on studies that are important to the development of metal casting at room temperature. In Chapter 3, the experimental setup that was utilized to get the desired results is described along with the methodology that was used to design the prototype. Chapter 4 concludes with reviewing the results from experiment.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Primarily, an in-depth examination of modern casting methods is vital to gain a thorough understanding of the casting techniques available. Analyzing the advantages and disadvantages associated with each method is essential to figure out the most appropriate casting approach for the given application. Furthermore, a comprehensive exploration of ink properties, particularly with regard to rheological behavior, holds significant importance. This investigation is pivotal for a precise prediction of ink behavior, thus enabling effective defect mitigation solutions.

Additionally, an in-depth study into the curing mechanisms within the casting process is imperative. A comprehensive understanding of the influence of various process parameters on the final product's quality is of paramount significance. Furthermore, a detailed examination of defects is important to understand both the factors contributing to porosity and the corresponding remedial measures.

2.2 Casting Methods

This section mainly focuses on room-temperature casting techniques, including cold casting, tape casting and slip casting, vacuum casting, room temperature casting and metal powder casting. The difference between casting materials like silicone and ceramics, which are normally cast at room temperature, and metals, which are typically cast at high temperatures, has been highlighted by recent study findings. The goal of researching the casting technique is to find out the benefits of the current casting processes that can be used as a model. The most crucial step is determining which casting technique is best for this project.

2.2.1 Cold Casting

The term "cold casting" describes the ceramics casting procedure without an initial heating stage. According to research, making slurry in three different densities and using room temperature to pour it into the molds, it was discovered that while a slurry with a higher viscosity has better mechanical properties. Reduced viscosity can indeed result in a cast product that is excessively brittle. However, it's important to note that lower viscosity may also lead to an inability to adequately fill the cavity (Boys and Walsh 2019).

As a result, it can be concluded that the viscosity of the slurry is an important factor that needs to be studied carefully.

2.2.2 Tape Casting/Slip Casting

Another casting technique used for ceramic casting is tape casting. According to research, Plasticizer and binder were combined with the ceramic powder. According to the results of the experiment, the slurry's viscosity decreases with increasing plasticizer tobinder ratios (Liu et al. 2012). Low tensile strength is caused by the decreased plasticizer to binder ratio (Cynthia M. Gomes et al. 2009). The results of a tape casting experiment in ceramics likewise indicated that slurry dispersion nonuniformity was insufficient to explain the morphology of the porous surface (Liu et al. 2012).

A common technique for casting ceramics is called slip casting, which involves layer-by-layer pouring of the ceramic material and removal of the liquid component subsequently. In the research, it has stated that the rheology of the liquid, the casting rate, and the possible appearance of shrinkage are a few of the variables that must be carefully taken into account while utilizing this method of casting. It is important to keep in mind that slip casting requires a lot of time (Yüzbasi and Graule, 2021).

The ceramics casting demonstrates the importance of density, tiny particles, and casting velocity because those factors are the causing parameters that affect the defect of cast products. Three different powders (1.8 -3.0 μm) are used varies of the casting speed at room temperature to study the shrinkage properties. It can be concluded that high casting velocities can reduce shrinkage variation by knowing the shrinkage variation decrease from 18.86% to 19.67%. Since metal powder and ceramic powder are both blended at room temperature, this is still relevant and useful for this project. Shrinkage is reduced when fine powder (<2.2 μm) and high density powder are used (Besendörfer et al. 2007a). In order to prevent particle settling, density must also be sufficiently high.

2.2.3 Vacuum Casting

Ceramics, silicone, resin, and other materials may all be cast through vacuum casting. In comparison to traditional casting techniques, it is a casting technique noted for improving surface quality and improving mechanical properties. This enhancement results from the vacuum process' capacity to remove gases out of the metal mixture. Low-pressure casting is also used to reduce gas porosity while improving mechanical qualities. The disadvantage of vacuum casting, however, is that it requires more time to cure than other casting techniques, which makes it less appropriate for mass manufacturing (Black and Kohser 2019). The experiment did indicate, however, that silicone molds' flexibility might result in deformation problems (Hambali Boejang 2009).

According to research on the vacuum casting with resin, shrinkage may be reduced and dimension accuracy can be improved when the resin is 30°C, the mold is 60°C, and the vacuum pressure is applied for 5 min. The dimension accuracy of the final cast product would be significantly impacted by vacuum pressure time as compared to resin temperature and mold temperature (Mohd Nazri Ahmad. et al. 2018). Instead, consideration must be given to the vacuum pressure time if vacuum casting is combined with other casting techniques.

2.2.4 Room Temperature Casting

It is mostly used in the casting of silicone materials for room temperature casting, also known as room temperature vulcanization. A 10% weight catalyst is combined with silicone rubber for 2 to 5 minutes. Before putting the silicone liquid into the casting frame, it is degassed for 10 to 15 minutes to eliminate any air bubbles. The silicone mixture is then degassed for an additional 25 to 35 minutes. Since it has been demonstrated that a hybrid of room temperature casting and vacuum casting provides dimension accuracy of the forms as well as surface polish (Tang et al. 2007), the same process may be used for this project.

2.2.5 Metal Powder Casting

Metal composition is the term used when metal is combined with other elements. Stir casting of an alloy of aluminum and silicon known as metal-metrix composites have been studied in one of the experiments. The Silicone in that experiment needs to be warmed to 750°C. The volume percentage of the cast product has an impact on its porosity, according to the experiment (Ahmad et al. 2005). Additionally, it was stated in that publication that the combination needed to be stirred since Silicone sinks in comparison to Aluminum, which has a density of 3.2 g/cm (LLOYD and JIN 2003). This project has a metal powder density of 7.8 g/cm and a binder density of around 1.3 g/ml. If mixing is ineffective, the solution cannot combine uniformly.

Additionally, some industry experts choose to cast a combination of resin and metal powder at room temperature while preserving a 1:1 volume ratio. According to common experiences, a thicker slurry is far more successful at casting larger components than a thinner combination when it comes to tiny pieces. In order to get rid of gas bubbles before putting the liquid into the mold, the author also suggests vacuuming the mixture. The poured mold is then put inside a pressure chamber and cured at 60 psi for four hours (Coetzee 2016). This project can include a review of certain casting methods, such as degassing the casting prior to putting it into the mold and curing the mold in a pressure chamber.

2.3 Ink Characteristic

Rheological behavior is the main topic of this subsection. To ensure equal mold filling, the flow parameters often referred to as liquid metal characteristics must be determined. By doing this, imperfections like porosity, gas bubbles, and imperfections can be reduced.

2.3.1 Non newtonian fluid

For easier discussion, it is crucial to classify the mixture into fluid models before going further into the fluid's rheological behavior. This is to have a better knowledge of rheological behavior and shear stress over shear rate. Non-Newtonian fluids and Newtonian fluids are the two primary categories of fluids. Yield-Pseudoplastic, Bingham Plastic Fluid, Pseudoplastic Fluid, and Dilatant Fluid are all considered non-Newtonian fluids, but Pseudoplastic and Yield-Plastic are classed under shear thickening, while Dilatant and Newtonian fluids are grouped under shear thinning (Nguyen and Nguye 2012).

2.3.2 Rheology Test

Rheology tests must be carried out in order to better forecast the flow behavior of this project and quantify the metal mixture. Several tests must be carried out in order to determine the rheological behavior, including the flow curve, amplitude sweep, frequency sweep, and Three Interval Thixotropy Test (3ITT).

The flow curve test is used to find viscosity models that show how shear stress and shear rate relate to one another (Fisher et al. 2007). The curve test can be used to determine which category has a non-Newtonian solution. Shear stress reduction and a rise in shear rate fall within the yield-Pseudoplastic classification. More accurate flow behavior predictions are made because to it (Tok et al. 2000). The Herschel-Bulkey model is proposed as follow:

$$\tau = \tau_Y + k(\frac{\partial u}{\partial y})^n \tag{1.1}$$

where

τ = shear stress, Pa

$\frac{\partial u}{\partial y}$ = shear strain rate, s^{-1}

k = consitency of the fluid, Pas^n

n = flow index, dimensionless

Meanwhile, the goal of the amplitude sweep test is to identify the yield stress, which shows that the solution cannot change back to its liquid or original form (Öhrlund 2018). The shear modulus G' (storage modulus) and G" (loss modulus) (Böhning et al. 2019)as well as ink stability (Nijdam et al. 2021) need to be measured using the frequency sweep test. The tension stored in the material is how the storage modulus is determined (Janmey and Schliwa 2008). From here, it can be done to understand how the flow will behave over time. While 3ITT enables the estimation of recovery rate and recovery percent, this also means that it has a rapid shear stress/shear rate measurement capability (Toker et al. 2015). To uniformly fill the mold without any gaps that might lead to imperfections during casting, the solution should have a more liquid consistency.

2.3.3 Relationship

The relationship of shear stress and shear rate is defined by

$$\eta = \frac{\tau}{\dot{\gamma}} \quad (1.2)$$

where

η = viscosity, $Pa\ s^{-1}$

τ = shear stress, Pa

$\dot{\gamma}$ = the shear rate, s^{-1}

2.4 Curing Mechanism

There are two types of curing mechanisms: chemical curing mechanisms and physical curing mechanisms. It is characterized as cross linking in terms of the chemical curing mechanism. Cross-linking is used to cure materials like sulfur, epoxy resin, and other materials (Akiba 1997).

2.4.1 Solvent Evaporation

Solvent evaporation refers to the physical curing process. Metals and ceramics are both subject to solvent evaporation. A combination of binder and acetone is used to turn metal powder into a liquid condition at room temperature. The interaction between the liquid and solid fractions is essential to the curing process. The metal powder remains unchanged during solvent evaporation while the liquid evaporates. Instead of the usual process of solidification, the metal powder goes through a phase transition from liquid to solid. The elements that influence the rate of evaporation will be studied.

2.4.2 Solvent Evaporation Time

The solvent evaporation rate is influenced by a number of variables. Knowing the variables that impact solvent evaporation time is essential since it has been demonstrated that these variables affect the membrane surface, which in turn determines defects in the cast result (Jami'an et al. 2016). Research demonstrates that when solvent evaporation duration increases, membrane surface porosity decreases and a thicker skin layer forms (Jami'an et al. 2016). It has also been demonstrated that a high solvent evaporation time causes a high drying rate at a surface, and this rapid and uneven drying rate causes cracks or inside shrinkage (Besendörfer et al. 2007b).

Additionally, because gas moves from bottom to top during rejection, it tends to gather towards the surface of cast products. However, because internal and external dry times are uneven, gas bubbles persist and result in gas defects (Besendörfer et al. 2007b). In order to prevent shrinkage and gas flaws, it is essential to maintain a sufficient solvent evaporation time.

2.4.3 Factors affect Solvent Evaporation Time

Concentration of the metal and binder has demonstrated that it can affect the rate of evaporation. Binder concentration has an impact on the solution's viscosity, and a higher solution viscosity results in a thicker film. Another element that influences the evaporation rate is the solvent content in the gas phase. Acetone evaporation rate decreases with increasing gas phase acetone concentrations (Miyazaki et al. 2006). Comparing acetone to other solvents such methyl enthyl ketone and cyclogexanone, it is a very versatile solvent (Chen 1983).

The solvent's thickness could be taken into account. Solvent evaporation rate decreases as solution thickness increases (Verros and Malamataris 2001). Additionally, temperature of mixture, the removal of solvent vapor, and the thermal environment are external elements that have a significant impact on the solvent evaporation rate (Chen 1983). Solvent evaporation rates rise as temperature rises (Miyazaki et al. 2006).

2.4.4 Gorvening Equation

The governing eqn.1.3 which is also known as Fickian diffusion, is a prediction used to calculate how diffusion causes the concentration to change with respect to time.

$$\frac{\partial \varphi}{\partial t} = D\frac{\partial^2 \varphi}{\partial x^2} \qquad (1.3)$$

where

D = diffusion coefficient, m^2/s

φ = concentration, mol/m^3

t = time, s

x = position, m

2.5 Defect

Numerous academics have conducted in-depth studies on cast defects in products. These imperfections include challenges like shrinkage and gas porosity, which will serve as the main topic of this chapter. For instance, microporosity might result in decreased ductility and fatigue characteristics (Blair et al. 2005b). To evaluate the quality of cast products, a variety of approaches are used. The relationship between porosity and mechanical properties can be clarified using a finite element study of stress and strain. Surface and volumetric defects can be detected by visual inspection, scanning electron microscopy (SEM) for surface inspection, and density measures (Blair et al. 2005b). Furthermore, the DOE method—more particularly, the Taguchi method—has demonstrated effectiveness in lowering sand-related errors from 10% to 3.59%, demonstrating its potential application to this project (Dabade and Bhedasgaonkar 2013).

2.5.1 Gas Porosity

Gas porosity occurs when gas bubbles get trapped during the curing process; possible causes include inadequate metal fluidity, a slow pouring rate, slag on the metal surface, and extremely thin metal sections. Modifying metal fluidity, speeding up the pouring process, and lowering mold gas pressure are all possible remedies for the problem (Vaibhav Ingle. and Madhukar Sorte 2017b).

Experiments have been carried out, according to Achamyeleh A. Kassie and Samuel B. Assfaw, to identify the optimal combination of process parameters limiting gas cavity development. In particular in steel casting, factors including mold permeability, binder type, and others play key roles when creating defects (Editorial Staff 2019). Sand to binder ratios of 100:1kg, mold permeabilities of 250–300, pouring temperatures of 1460–1490°C, and deoxidant concentrations of 0.2% provide the best results for sand casting. The conclusion is that particular environmental and working factors have an impact on the causes of gas problems. Consequently, more accurate findings and a better understanding of individual parameters would arise from increased knowledge about defect-causing factors. Although molten metal and sand casting were used for that experiment, Taguchi's method of reducing gas porosity to identify potential causative factors is still useful to this experiment (Kassie 2013). This project can apply the Taguchi method learned from that experiment.

Additionally, the homogeneity of combinations has a considerable influence on the final cast product which often results in porosity because of uneven distribution of the binder components. Longer mixing durations provide a more uniform and homogenous mixture, as shown by R.L. Naro's tests, which included modifying the time for mixing various components (RL Naro 1999). The extended mixing time to increase homogeneity can still be employed in the planning stage of this experiment, even though Naro's trials used different materials (iron and resin) than those in this project.

Additionally, the molds employed in this project don't have adequate permeability to allow gasses to be rejected from the casting solution. As a result, it is another factor contributing to the occurrence of gas porosity.

2.5.2 Shrinkage

Shrinkage is caused by differences in density between liquid and solid phases (Abdul Haseeb NC et al. 2015). The material decreases in size when a phase shift takes place. Ensuring that liquid metal keeps flowing into voids as they occur is the standard method for removing shrinkage porosity (Vaibhav Ingle. and Madhukar Sorte 2017b; Besendörfer et al. 2007b). A careful design of the gating and riser can reduce the faults and help avoid shrinking (Sahoo and

Goswami 2023). Reduced shrinkage can also be achieved by quick solidification (Sahoo and Goswami 2023).

In order to avoid volume reduction, the pouring methods and angle must be carefully considered to provide a constant supply of casting solution. Additionally, the solidification time must be carefully controlled because if the solvent evaporates too quickly, gas cannot be drawn out of the solution, while a long solidification time results in shrinkage.

2.5.3 Blowhole

The blowhole occurs as a result of the metal's molten state's gas emissions and the metal's carbon and hydrogen reacting with oxygen (Abdul Haseeb NC et al. 2015). The mechanical characteristics of cast products will be impacted by the same factors that determine gas porosity. Normally, during the solidification process, hydrogen and nitrogen gases are involved. Additionally, it was stated that smaller castings solidify more quickly than larger castings, preventing hydrogen from escaping because of the too-short solidification interval. To emphasize another point, water is the source of hydrogen (Abdul Haseeb NC et al. 2015). As a result, it may be said that DI Water is not appropriate for this project.

The temperature and humidity have a significant impact on the solubilities of hydrogen in steel. More porosity will result from higher humidity (Blair et al. 2005a).Vacuum pumps are a highly practical approach to enhance blowholes; they have shown that the quality may be raised. The blow hole can be reduced by low pressure (Nitin Rajaram Bhone 2004).

2.5.4 Cold shut

The causes of cold shut may be divided into four categories: material, procedure, human mistake, and machine error. Low pouring temperatures have been said to result in cold shuts. Additionally, incorrect pouring technique or interruptions during pouring will result in cold shut. Additionally, one of the factors that contribute to chilly shut is an inappropriate getting system (VV Mane et al. 2010). To avoid this problem in this project, above mentioned factors have to be taken carefully.

2.5.5 Mismatch

Any mold movement or misalignment will result in a mismatch. While carefully clamping the mold is one technique to enhance (VV Mane et al. 2010; Abdul Haseeb NC et al. 2015).

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

Methods and workplan that are used to complete the project and achieve the objectives of this project are discussed in this chapter. From the literature review and consultation from experts in the fields, it is found that there are several critical causing parameters that will affect the final casting product and cast defects. As a result, the causing parameters involves permeability, rheological behaviour, formulation of mixture, and mold thickness.

Workplan includes flow chart of this project, gantt charts that clearly show the planning of work plan conducted throughout the year. The flow chart of this project shown in Figure 3.1.

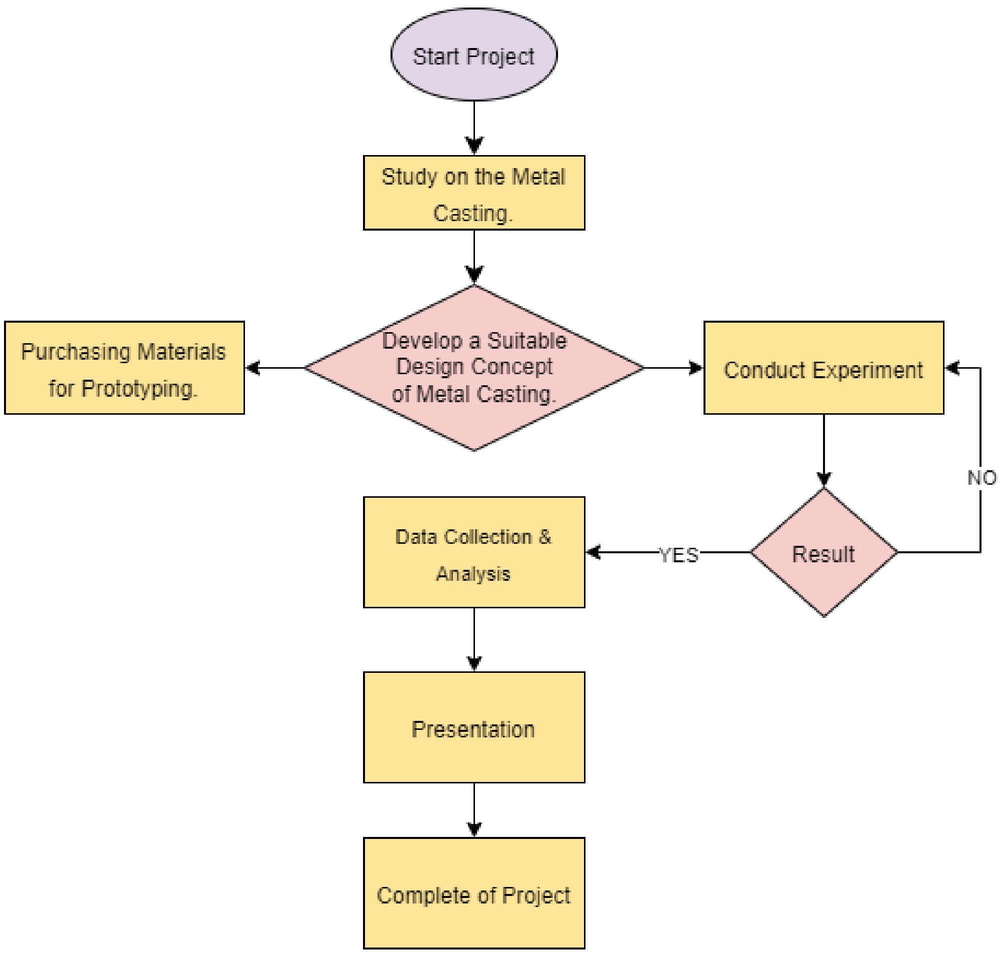


Figure 3.1: Flowchart of the project

3.2 Experiment Method

To accomplish the objectives of this project, the Taguchi Method has been applied for Design of Experiments (DOE). As previously indicated, the Taguchi Method stands out as the best choice when involved with numerous unknown independent variables within a process, with their respective influences remaining unknown. Table 3.1 shows the probably independent variables so that the individual influence can be known from this project.

Table 3.1: Independent variables in metal casting.

Formulation Section	Curing Section
Acetone (wt%)	Vacuum Casting
Cellulose Deriavative Binder (wt%)	Ambient Casting
Plasticizer (gram)	Heating Casting
Deionized Water (gram)	

Furthermore, Rheology tests will be conducted to quantitatively assess flow behavior. Rheology test includes four different tests namely flow behaviour, amplitude sweeps, frequency sweeps and three interval thixotropy (3ITT). This examination will ensure the consistent production of high-quality castings.

Indeed, the above-mentioned individual variables stated in Table 3.1 do not stand alone in influencing defects such as shrinkage and gas bubbles in the castings. The thickness of the silicone mold, choice of binder, and casting method are also substantial contributors to such imperfections. However, within the limit of this chapter, the primary emphasis is placed upon the formulation of each component, given its paramount importance in achieving the defined objectives.

After a thorough examination, the decision has been made to include formulation ratios as the designated parameters within the experimental framework. These formulation ratios have been categorized into three distinct factors, each contains four levels. Table 3.2 also shown the level of each parameters that will be varying the process.

Table 3.2: Selected parameters with different level of formulation.

	Binder ratio (wt%)	Plasticizer (vol%)	Di Water (vol%)
Level 1	0.75	3	2
Level 2	1	6	4
Level 3	1.25	9	6
Level 4	1.5	12	8

3.3 Experiment Setup

Procedure to conduct experiment such as mixing procedure will be discussed in detailed in this chapter.

The experimentation commences with the introduction of metal powder into the binder and or other causing parameters stated in Table 3.2. Once the components are combined, the mixture will then be weight using a precision balancer, followed by the utilization of a stirrer to homogenize the mixture, refer to Figure 3.2 & Figure 3.3.

Figure 3.2: Precision Balancer

Figure 3.3: Stirrer

Subsequently, this homogenized mixture is gently poured into silicone molds. Figure 3.4 is the mold that will be used in the project which is a silicone ice cub mold that is able to withstand Acetone.

Figure 3.4: Silicone Mold

After the metal mixtures is poured into the mold, 20 ml of mixture of each sample will be taken for Rheology Test. Notably, prior to the molds' placement in the desiccators, a strategic application of Acetone onto the cast product's surface is undertaken, refer to Figure 3.5. The desiccators are then employed to evacuate any residual gases, thus creating an environment conducive to curing. The cast product is subsequently allowed to rest at ambient temperature until it fully cures, a process that extends into the following day.

Figure 3.5: Desiccator

Only once this curing process is complete, demoulding of the cast product will be proceed. The general setup for the experiment is stated clearly in Table 3.3.

Table 3.3: Overall setup for metal casting at ambient temperature

Stirrer	
RPM	300
Time	10 minutes
Vacuum	
Vacuum Time	10 minutes
Dry time	24 hours

The last step is observation. The observation involves sectioning the cast product into multiple segments, pictures will also be taken for different views of the samples such as top view, bottom view, and internal view, refer to Table 3.4. These segments are scrutinized under a scanning electron microscope (SEM) to meticulously analyze their internal structures, with particular attention given to porosity. The insights and data gleaned from this examination are thoughtfully compiled and presented in tables and graphical representations, as elucidated in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In order to prove the design concept, several experiements have been proceeded. Before running other experiments such as Rheology test, design of experiment via Taguchi Method has been carried out to obtain the optimized formulation. Density of green parts and sintered parts have been measured. Impact of the evaporation time on output and sendiment test have been carried out to obtain its performance at different percentage of Acetone on the defects. After obtaining the optimized formulation, the mechanical properties is proceeded.

4.2 Taguchi Method

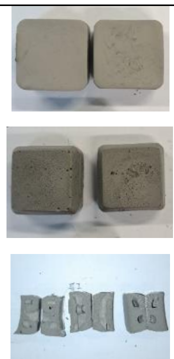
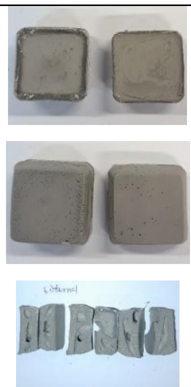
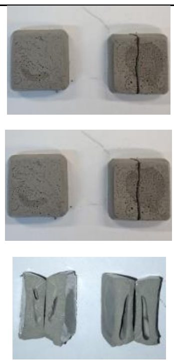
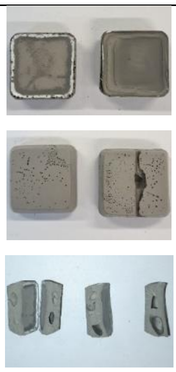
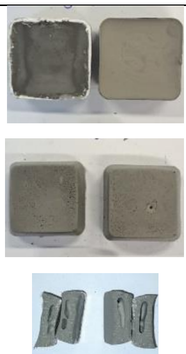
The design of experiments via the Taguchi Method helps determine the optimized formulation. According to Table 4.1, 3 parameters and 4 levels were tested using the same procedure.

It can be seen from Table 4.1, compare Sample 1 to Sample 4 proves that the best surface finishing is Sample 4. When binder is below 1 wt%, it is powdery, fragile and difficult to demould, which eventually leads to low mechanical properties. The internal porosity of Sample 4 is much more better than Sample 3. Therefore, the binder concentration of 1.5 wt% is preferable.

Additionally, plasticizer improves the flowability of the slurry. Plasticizer were added from 3 vol%, 6 vol%, 9 vol% and 12 vol%. Plasticizer has greatly improved the flowability of the slurry therefore the slurry can fill the shape of the mould. Besides, the surface finishing of the cast products after adding Plasticizer (Sample 5~Sample 8) has greatly been improved and it is not fragile compared to Sample 1~4. However, only above 6vol% of Plasticizer can improve the porosity of the cast product. It can be proved from Sample 6 and above. Besides that, the samples are not powdery and it is easier to be demould compared without adding Plasticizer.

From Sample 9~12, the cast products were added deionized water from 2 vol% to 8 vol% without plasticizer. However, deionized water demonstrates no improvement in surface finishing, porosity, and internal defects.

Table 4.1: Pictures of the Cast Product.

Metal: 60 vol% Binder: 0.75 wt%	 Sample 1	Metal: 60 vol% Binder: 1.5 wt% Plasticizer: 3 vol%	 Sample 5	Metal: 60 vol% Binder: 1.5 wt% DIW: 2 vol%	 Sample 9
Metal: 60 vol% Binder: 1 wt%	 Sample 2	Metal: 60 vol% Binder: 1.5 wt% Plasticizer: 6 vol%	 Sample 6	Metal: 60 vol% Binder: 1.5 wt% DIW: 4 vol%	 Sample 10
Metal: 60 vol% Binder: 1.25 wt%	 Sample 3	Metal: 60 vol% Binder: 1.5 wt% Plasticizer: 9 vol%	 Sample 7	Metal: 60 vol% Binder: 1.5 wt% DIW: 6 vol%	 Sample 11
Metal: 60 vol% Binder: 1.5 wt%	 Sample 4	Metal: 60 vol% Binder: 1.5 wt% Plasticizer: 12 vol%	 Sample 8	Metal: 60 vol% Binder: 1.5 wt% DIW: 8 vol%	 Sample 12

Therefore, it can be concluded that the optimal range for the castability of this project is showns in Figure 4.1.

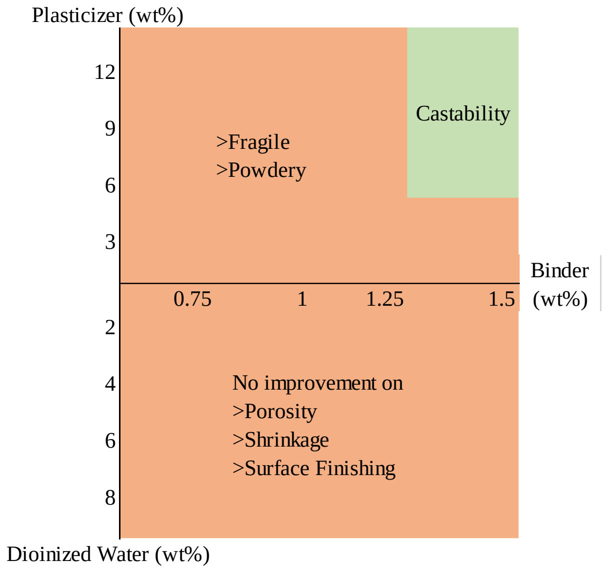


Figure 4.1: Castability Region

4.3 Density

Density can help proving whether internal porosity has been eliminated. By conducting this test, the formulations from Table 4.1 can be quantified. Applying a formulation of 60 vol% of 17-4 PH metal, 1.5 wt% of binder, and 6 wt% of plasticizer, it can be observed from Table 4.2 that the density for both green and sintered samples is above 90%, which is considered high, indicating that entrapped air bubbles are not significant.

Table 4.2: Density of green part and sintered part

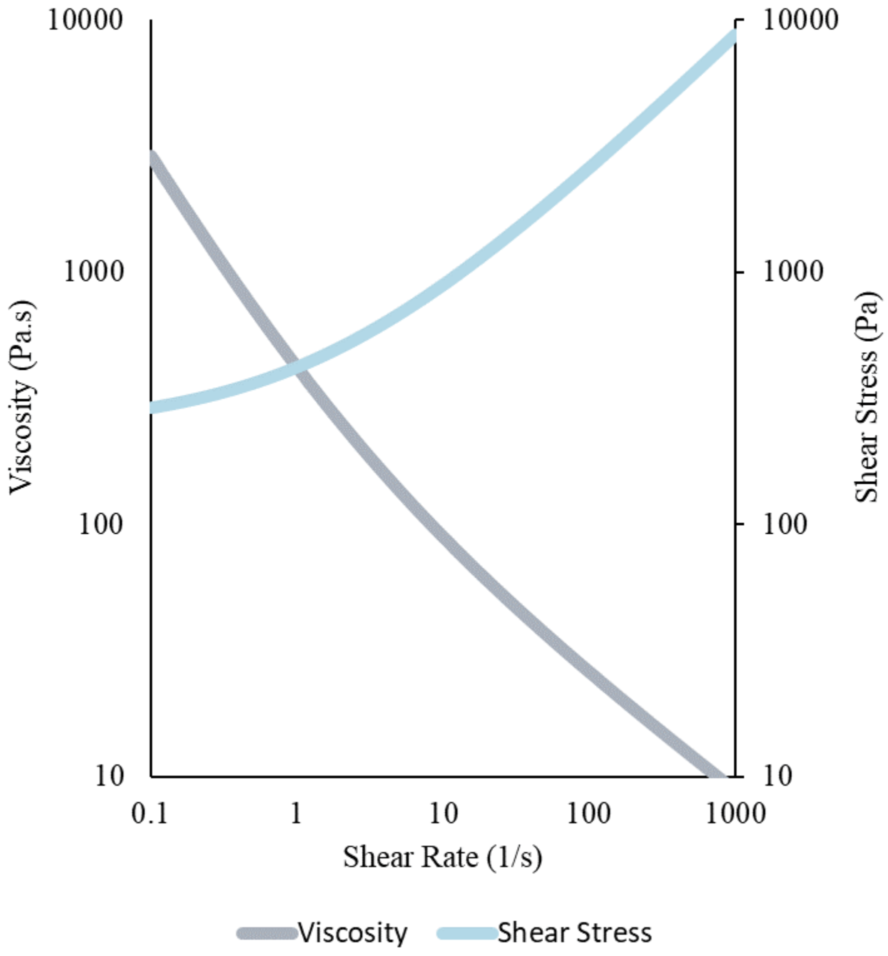
	Green Part	Sintered Part
Relative Density (%)	92.74	91.23

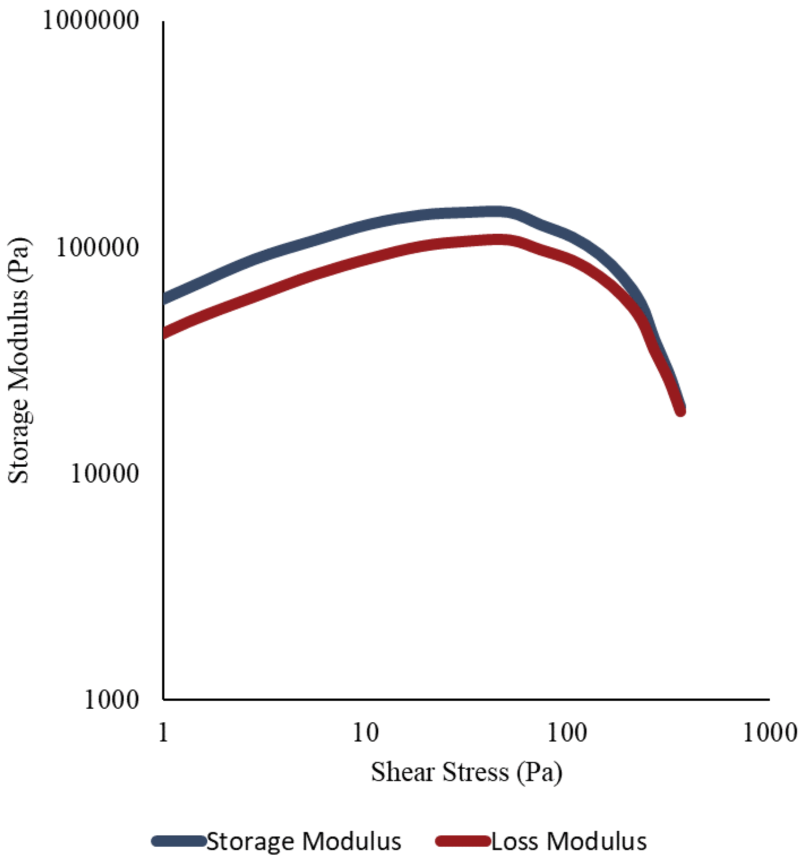
4.4 Cast Product Characterization

To categorized the properties of the optimized formulation, Rheology test, drying test, sendiment test and hardness test have been conducted.

4.4.1 Rheology Test

Based on the computed result for shear rate and fluid viscosity, this validates non-Newtonian fluid which is Hershel-Bulkley according to the rheology data (Figure 4.2) and Equation 1.1. The vicsosity is 89.741Pas when the shear rate is 10.8s^{-1} (Figure 4.2(a)). Besides, it can be shown that the yield stress of this slurry is 51.496 Pa (Figure 4.2(b)). The sendiment happens at 0.0631Hz (Figure 4.2(c)).





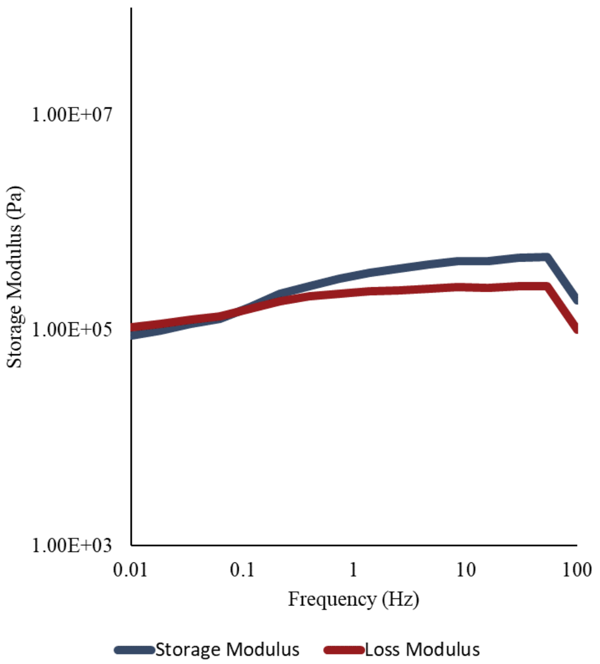


Figure 4.2: (a) Flow Curve; (b) Amplitude Sweep; (c) Frequency Sweep

4.4.2 Impact of the evaporation time on the output

The impact of the evaporation time can greatly impact the output. Vary concentration of Acetone has been added on top of the slurry at ambient to test the evaporation time. From Figure 4.3, it shows that higher concentration of Acetone can lower the evaporation rate. Therefore, lesser binder will be float on the top and it can be more campact.

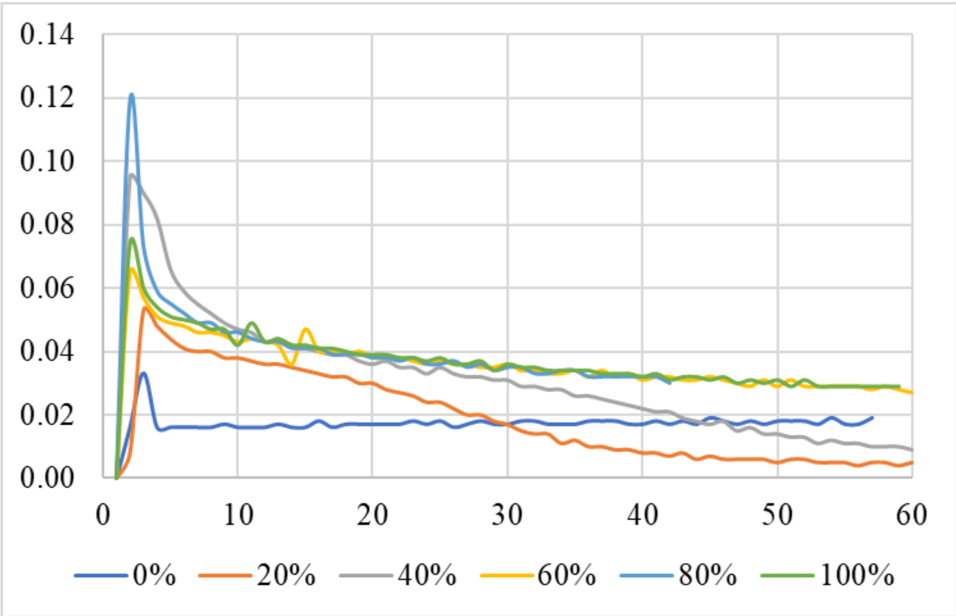


Figure 4.3: Evaporation Time

4.4.3 Impact of the Binder on the output

The impact of the binder on the output have proven that can affect the sendiment of the slurry and eventually affects the outcome. The concentration of binder is vary from 1.3 wt%, 1.5 wt% and 1.8 wt%. From Figure 4.4, it shows the remaining weight of binder after 24 hours of dyring process. As the concentration of binder increase in the solvent, the decrease of the weight in the remaining binder. The lesser the binder sendiment from the slurry, the compact the cast product it is. In conclusion, higher concentration of binder leads to a better result which again proves the formulation of this project is castable and workable.

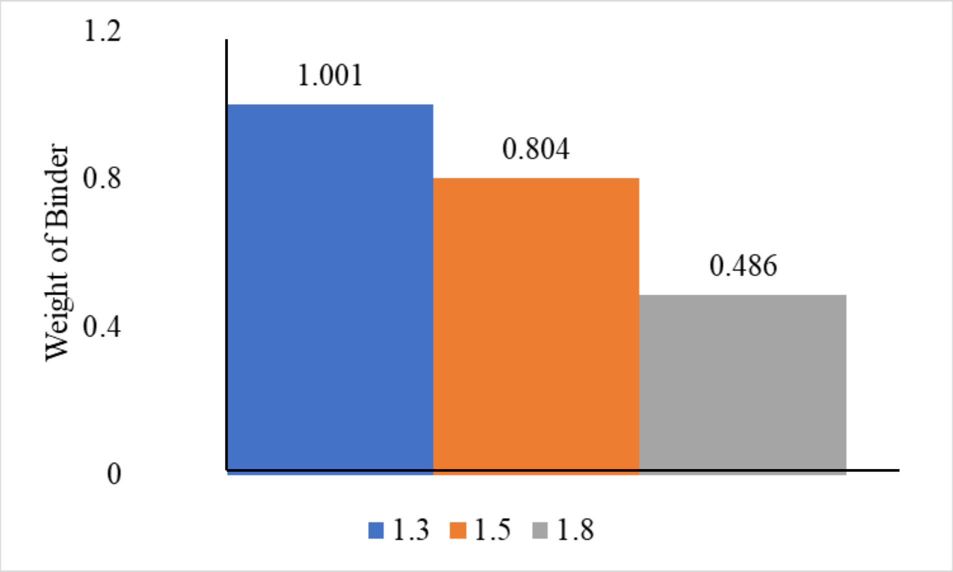


Figure 4.4: Evaporation Time

4.4.4 Microstructure

Based on Figure 4.5, the microstructure of the cast product validates with 17-4 PH stainless steel theoretical result (Figure 4.5(c)). The cast product is sintered at 1350℃ at 2 hours with atmsphere vacuum condition of 20% argon gas. It contains martensitic, ferrite and defects (Figure 4.5 (b)).

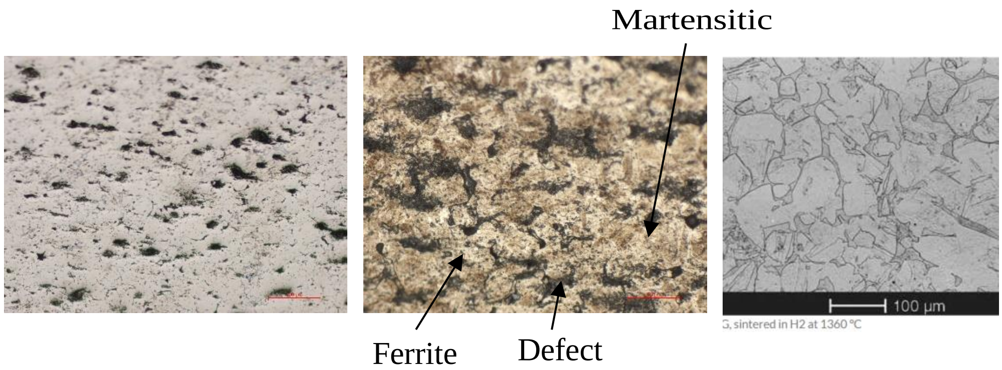


Figure 4.5: SEM micrographs of 17-4PH sintered at 1350℃, (a) before etching; (b) after etching; (c) theoretical result.

4.4.5 Hardness

The hardness of the cast project is determined by Rockwell hardness scale (RHC), the average hardness in this outcome is 16 HRC. However, the hardness needs to be improved to enhance the reliability and performance of the cast products.

4.5 Different mold material on the output

Based on Figure 4.6 it shows that the 3D resin material mold can be casted using these casting method. This has proven that both silicone mold can 3D resin mold can be cast.

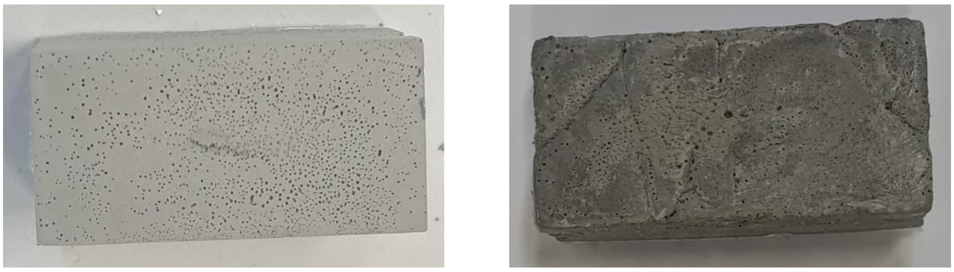


Figure 4.6: Surface finishing of cast product using (a) silicone mold; (b) 3D resin mold

However, it is difficult to demould when using 3D resin mold. Besides that, using 3D resin mold is not having good surface finishing. Therefore, 3 different coatings including Petrolatum, Silicone and PTFE are tested to observe that which is the easiest to be demould. Figure 4.7 shows that Silione coating is better than the others.

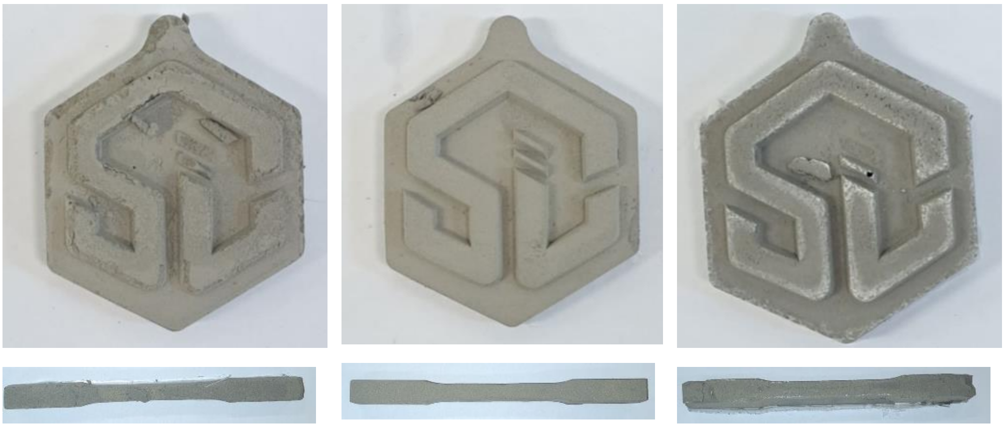


Figure 4.7: The outcome of (a) Petrolatum; (b) Silicone; (c) PTFE

4.6 Summary

A total of 12 sample were being experimented in the testing applying design of experiment via Taguchi Method. There are total 3 parameters with 4 levels. The optimized formulation is shown in Table 4.3. Additionally, the inclusion of plasticizer has significantly improved slurry flowability and product quality.

With this formulation, surface finsihing, porosity, fragility, powdery and shrikage can be minized.

Density measurement further support the validation of formulations, with densities above 90% and above, indicating minimal air entrapment in both green and sintered samples. Various tests including rheology, drying, sendiment and hardness test have provided insights into the cast products' properties. These tests validates non-Newtonian fluid behaviour (Table 4.4), and understanding the impact of the binder concentration on sendimentation and product compactness.

Microstructural has confirmed the alignment of the cast products with the tehoretical expectation, also further validating the effectveness of the formulations. Moreover, it again proves that the compatility of casting methods with different mold materials. However, challenges including the demolding difficulty and surface finishing issues when using other mold such as 3D resin molds. Besides that, silicone has been proven that the most efective solution for improving demolding ease.

In short, these findings provide valuable insights for optimizing the formulation and processing methods.

Table 4.3: Optimized formulation of metal casting at room temperature

	Metal (vol%)	Binder (wt%)	Plasticizer (wt%)
Castability Region	60	1.5	6

Table 4.4: Shear rate and viscosity for this formulation

Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (Pas)
10	891.47	89.147

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In summary, this project successfully achieved its primary objective of maximizing the ratio of independent variables to achieve 80% density in the green parts. Through meticulous experimentation and optimization using the Taguchi Method, a formulation was devised that not only met but exceeded expectations, yielding green and sintered densities exceeding 90%. This accomplishment underscores the castability of the formulation and demonstrates minimal porosity, crucial for ensuring the integrity of the final product.

Furthermore, the study delved into assessing the mechanical properties of the cast products, primarily through hardness tests. While the obtained average hardness of 207 HV signifies a promising foundation, it also highlights the necessity for further enhancement in subsequent research endeavors.

Additionally, the Rheology test provided valuable insights into the flow characteristics of the slurry, confirming its suitability for mold filling and adherence to the Herschel-Bulkley model. The determined viscosity ensures optimal flowability, essential for achieving consistent casting results. The sedimentation and phase change phenomena observed during testing warrant further investigation to refine the casting process.

Moreover, the project explored the impact of different materials and thicknesses of molds on the density of green parts, shedding light on crucial variables influencing the casting process.

In conclusion, this study affirms the feasibility of metal casting at room temperature, provided the formulation remains within the castable region. The findings underscore the importance of optimizing mechanical properties for broader applicability. Moving forward, efforts will focus on refining the formulation and process parameters to enhance versatility and efficacy in diverse applications.

5.2 Recommendations for future work

As we conclude our final year report on the project, it is imperative to acknowledge areas where improvements can be made to enhance the overall efficacy and quality of our work. Through our current findings, several key aspects have been identified for future refinement.

Firstly, the problem of hardness within the metal parts has been an issue. It shows that the current level of hardness is insufficient to withstand the stresses these parts may encounter. To address this concern, ongoing research and development efforts need to be focused on identifying suitable methods to enhance hardness. One potential avenue for exploration is the adjustment of binder levels, as this has shown promise in improving the hardness of similar materials in the past.

Secondly, the consistency of surface finishing has been identified as an area requiring attention. In order tomantain high standards of quality, it is essential that efforts be made to improve the uniformity and overall appearance of surface finishes. This may involve refining processes, implementing stricter quality control measures to effectively address the issue.

Furthermore, there is a need to consider the potential for customizability within the mold design. By exploring opportunities to produce the mold to accommodate various shapes and configurations, it can promise the versatility and adaptability of the cast product. This may involve implementing modular components, adjustable features, or other innovative solutions to facilitate customization.

In conclusion, it is imperative that to remain proactive in addressing these identified areas for improvement. By dedicating resources and attention to these challenges, overall effectiveness can be improved.

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APPENDICES

Appendix A: Graphs

Appendix A-1: Cast products of sintered part and green part.

Appendix A-2: Cast product of sintered part.

Appendix A-3: Set up of sendiment test with different concentration of Acetone