PROCESSABILITY OF WASTE PLASTIC BAG AS A NOVEL BINDER SYSTEM IN METAL INJECTION MOLDING

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PROCESSABILITY OF WASTE PLASTIC BAG AS A NOVEL BINDER SYSTEM IN METAL INJECTION MOLDING PROCESS

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A thesis submitted in fulfillment of the requirement for the award of the Degree of Master of Mechanical Engineering

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Special dedicated to my family who give me support:

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Metal injection molding is the most cost effective processes in powder metallurgy to produce small and intricate part for mass production. Many researchers are mainly focused on the commercial binders, while only few of them are conducting the MIM using recycle binders. Therefore, this work focuses on the characterization of waste plastic bag as a novel binder system with combination of palm kernel (PK) in “Green MIM” of 316L Stainless Steel. Significant with this, this effort was able to reduce MIM cost, reduce disposal problem and thus, create awareness among community that waste product can also be considered as valuable things instead of disposing them. However, this work was not covering the cleaning process of the waste plastic bag (WPB). The feedstock was prepared by three formulation of 50/50 (WPB/PK), 40/60 (WPB/PK), 30/70 (WPB/PK), while keeping 60 vol. % of powder loading. Homogeneity and rheology test prove that the all formulations were qualified to proceed in molding process. The screening test of molding process was conducted via Analysis of variance. It prove that the interaction factor was not significant to the responses. The combination of orthogonal array Taguchi L9 (3^4) and Grey Taguchi show that the optimal condition for conducting this process was; injection temperature of 180 °C, mold temperature of 50 °C, injection pressure of 40 % and injection speed of 50 %. Whereby, extraction in heptane solution (solvent to feed ratio of 12:1) at 70 °C within 7 hours was recognized as the optimal condition for solvent debinding. Else, a thorough study was conducted to investigate thermal debinding and sintering. The free defect of brown and sintered parts were produced. It was produced at 1360 °C by 1 °C/min within 240 minutes of soaking time in argon tube furnace. It was recorded the high strength of 782.48 MPa and 154.96 hv. Overall, this work revealed that the potential of using the waste plastic bag as a green binder for 316L Stainless Steel of MIM was achievable.
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<tr>
<td>FOG</td>
<td>Fat oil grease</td>
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<tr>
<td>FTIR</td>
<td>Fourier Transform Infrared Spectroscopy</td>
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<tr>
<td>GRC</td>
<td>Grey Relational Coefficient</td>
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<tr>
<td>GRG</td>
<td>Grey Relational Grade</td>
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<tr>
<td>HAP</td>
<td>Hydroxyapatite</td>
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<td>HDPE</td>
<td>High Density Polyethylene</td>
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<tr>
<td>LDPE</td>
<td>Low Density Polyethylene</td>
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<td>MIM</td>
<td>Metal injection molding</td>
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<td>Mn</td>
<td>Manganese</td>
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<td>Mo</td>
<td>Molybdenum</td>
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<td>NHAP</td>
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<td>Ni</td>
<td>Nickel</td>
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<td>O</td>
<td>Oxygen</td>
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<td>PE</td>
<td>Polyethylene</td>
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<td>PEG</td>
<td>Polyethelene Glycol</td>
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<td>Description</td>
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<td>Polystyrene</td>
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<td>PKO</td>
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<td>PMMA</td>
<td>Polymethylene Methacrylate</td>
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<td>PP</td>
<td>Polypropylene</td>
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<td>PW</td>
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<td>SA</td>
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<tr>
<td>SF</td>
<td>Sewage fat</td>
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<td>S/F</td>
<td>Solvent to feed ratio</td>
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<td>Si</td>
<td>Silicon</td>
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<tr>
<td>S/N</td>
<td>Signal to noise</td>
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<td>SS316L</td>
<td>Stainless steel 316L</td>
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<tr>
<td>Ti-6Al-4V</td>
<td>Titanium alloy</td>
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<tr>
<td>TPNR</td>
<td>Thermoplastic natural rubber</td>
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<tr>
<td>WPB</td>
<td>Waste plastic bag</td>
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<tr>
<td>TGA</td>
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CHAPTER 1

INTRODUCTION

1.1 Introduction

Metal injection molding (MIM) has been recognized to produce small and intricate part in high volume mass production [1-3]. It was being a versatile technology that can be used for a variety of alloys and ferrous metals such as carbonyl iron, iron-nickel, various stainless steels, titanium, tungsten and tungsten heavy alloys, as well as, intermetallic compounds [1,4]. Also, it becomes a promising technology since it can produce part with a high anti corrosion, having excellent mechanical properties such as strength, hardness and such on [5-6].

In MIM technology, fine metal powders are mixed with suitable thermoplastic binder and formed into the desired shapes [7-8]. The binder provides the flow ability and formability for the fine metal powder during injection molding [5]. Then, both are removed in the next processes that called debinding. The debinding process was purpose to obtain a higher density part. Often, it was conducted by two stages of removal, which are solvent extraction and thermal pyrolysis. After that, the components are sintered in order to form strong metallic components which can be produced by ensuring the pore-free structures is prepared. This process is able to produce the components that approaching closely to its theoretical density value.

1.2 Background of research

Previous research has been done by Agote et al. used the recycled powder in ceramic injection molding [9]. The recycle porcelain was used as a powders with combination
of the commercial binders for injection moulding. The waste porcelain application has a remarkable economic and environmental benefit. Regarding to Critical Powder Volume Concentrations (CPVC) and rheological tests, Agote et al. believed that it was possible to used recycled porcelain in the ceramic injection molding instead of using the commercial porcelain that is expensive.

Also, Ibrahim et al. worked on the MIM of Stainless Steel 316L that applying the Natural Hydroxyapatite (NHAP) as a minor powder. The bimodal system was well blended with binder system that comprised of commercial Polyethylene and palm stearin [10]. The NHAP was made by synthesizing the waste Tilapia fish bones. As known, the Hydroxyapatite (HAP) is a high biocompatibility materials due to its composition was nearly closed to the human bone. It is a valuable material that have a high cost to effort it. So that, this application of NHAP can reduce the manufacturing cost instead of using the commercial hydroxyapatite which is costly. Thus, they were investigated the process ability of natural HAP and SS316L mixture with commercial binders as a feedstock in MIM. It was claimed that the mixture (feedstock) was successfully injected and it was established as an appropriate feedstock in MIM.

While, previous study by Omar et al. applied waste rubber (from rejected gloves) as a binder for MIM technology for 65 vol. % powder loading of Stainless Steel 316L [11]. This previous study found that the feedstock was injectable and the final density was achieving the 99 % of the theoretical values. It was highlighted that the best sintering temperature for obtaining highest mechanical and physical properties was at 1360 °C.

Beside that’s, Amin et al. used the environmental substances which is the sewage fat (SF) as one of the binders system with combination of the Polypropylene (PP) and Stainless Steel 316L as a metal powder in metal injection molding [1]. SF has shown a great potential of being used as the major binder component for MIM process after undergo several major test such as mixing homogeneity and rheological properties.

Also, Asmawi et al. applied the recycle binder which is waste polystyrene blended with palm kernel oil (PKO) and SS316L [12]. The core idea of previous study is to apply the “Green MIM” which is environmental friendly. As known, the waste polystyrene was greatly used as food packaging. In this regards, this effort was able to reduce disposal problems.
Thus, author decided to use waste plastic bag as a binder source of commercial High Density Polyethylene. Author believed that such waste was able to be a more beneficial industrial products. Consequently, this research is focusing on the “Green MIM” in order to reduce the manufacturing cost while decreasing the residue materials and to widen the recycled product. In that sense, the overall aims of this research is to produce the perfect final part by using the waste plastic bag as a binder without any defects and thus contributes to the sustainability of the earth.

1.3 Problem statement

For many years, developing of newly binder system often being the major attention among the researchers in order to enhance the MIM technology while keeping the sustainability of the earth. This efforts has headed to several enhancements which are cost reduction, reduce environmental problems and much more. So far, broad exploration has been present by using natural resources binder, nevertheless only few of them are focusing to the waste resources binder. Nowadays, tons of waste plastic bag are disposed daily and it was getting worse when there are no alternative ways in recycling the waste systematically. Hence, due to this fact had motivated the author to reuse the waste plastic bag and transformed it into a more valuable industrial products such as a backbone binder system in MIM, instead of using the commercial High Density Polyethylene (HDPE). Even though this type of binder is cheap and having high dimensional stability due to the crystallinity structure [13], but it is non-biodegradable material which is difficult to dispose them. As reported by Nemade et al., the waste plastic bag is known as a source of HDPE, therefore in this study the waste plastic bag also used as the backbone binder system in “Green MIM” [14]. Although, the cleaning process of waste plastic bag involve a larger cost compared to use the commercial HDPE, beside can creates awareness among community that waste product can also be considered as valuable things instead of disposing them. Also, author classified this as a delicate effort since the fact shows that HDPE was a non-biodegradable materials, and they might cause air pollution by burning it, yet introducing a disposal problem since it was daily produced in a tons amount and may affect the human health. Indeed, author have limited this research work by excluding
the cleaning process of the waste plastic bag. So that, the new and clean waste plastic bag are used.

In fact, by implementing of this waste in MIM is not sacrificing its function as a backbone binder system which acts as a shape retention of metal part. Therefore, in this study the waste plastic bag was characterized to analyze the properties of the backbone binder system in MIM which practically having the similarity to the commercial HDPE. Also, in order to determine the flow ability of molten feedstock at a range of temperature, the rheological behavior of the feedstock has been conducted.

Practically, Li et al., Adames, Vielma et al., Huang and Hsu, Raza et al., Patil et al., Ibrahim and Kamarudin claimed the effectiveness of commercial HDPE as a backbone binder system in MIM [15-20]. So, how about the waste plastic bag performance?

1.4 Objectives

The objectives of this research are:

a. To characterize the binder system via Fourier Infrared Spectroscopy, density and thermal test.

b. To evaluate the feedstock performance via rheological test, density, binder burnt-out test and scanning electron micrograph.

c. To optimize injection molding process (by evaluating the green density and strength) and solvent debinding process (by evaluating the palm kernel loss and solvent part’s density) via Taguchi Method.

d. To measure value of thermal debinding (by considering brown density and morphology) and sintering (by considering final part’s density, tensile strength, hardness, morphology and shrinkage).

1.5 Scopes

The scopes of this study were focused on:

a. Palm kernel (PK) and waste plastic bag (WPB) were selected as a binder system and Stainless Steel 316L (SS316L) act as metal powder.
b. The new clean WPB is used. Thus, the cleaning process of WPB was not covered in this research.

c. The binder composition of 50/50 (WPB/PK), 40/60 (WPB/PK) and 30/70 (WPB/PK) and the constant powder loading of 60 vol. % were used.

d. Investigating the mixing procedure of SS316L, PK and WPB.

e. Measuring the acceptable volume ratio between binder system and metal powder via rheological test.

f. Optimization of green part (by considering green density and green strength) via density test (Archimedes’ Principle) and three-point bending test (according to ASTM Standard SI 10 as being referred in Metal Powder Industries Federation 15).

g. Investigating the solvent debinding in order to assess the palm kernel diffusion through Scanning Electron Microscopic (SEM).

h. Optimization of solvent debinding (by considering the palm kernel loss and solvent part’s density) via percentage of PK loss and density test (Archimedes’ Principle).

i. Evaluation of brown part (part called after thermal debinding) by examining the density (Archimedes’ Principle). Besides that, the microscopic structure of the part is observe by SEM.

j. Evaluation of final part (part called after sintering) by determining the parts density (Archimedes’ Principle), tensile test (according to ASTM Standard E8 as being referred in Metal Powder Industries Federation 10), hardness test and shrinkage. Also, the microscopic structure of the part is observe by SEM and optical microscope.

1.6 Significant of study

Nowadays, there are tons of waste plastic bag produced every day. Even, many countries are having a critical disposal problem. It will turn worsen when no alternative ways are conducted for managing the disposal problems. Moreover, it is become a crucial problems because of its great interconnection with the healthy level of humans, animals and plants.
Instead of burning (which are able to produce damage gases such as carbon monoxide, nitrogen oxide, sulphur oxide, etc.) and having disposal problem, the effort of reuse the waste plastic bag as a binder system in metal injection molding was claimed as a great effort in order to overcome this several problems. In addition, the MIM is relatively new in Malaysia and it gives a great opportunity for those researchers that conducting this research. Perhaps this technology can be exploited in Malaysia in future for the benefits of all industrial sectors. To date, developing of a new locally binder system can be consider as a great concern where it was beneficial to the local industry. Beside that’s, many attempts have been made in developing a new binder system that focused on the cost reduction and shorten production process.

Significant with this, the potential uses of palm kernel and waste plastic bag as a binder system for producing a better quality feedstock was investigated. Also, this research demonstrates the great effort for a better finding in the future research purpose to explore the “Green MIM”.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter details focus on presenting the metal injection molding (MIM) technology specifically on the metal powder properties, binders system, binders and feedstock characterization, optimizing injection molding and solvent debinding processes, investigating thermal debinding and sintering. Overall, this chapter discussed the possible parameters and ways that need to be includes in all the processes in order to fulfil the objectives of this research. The specific requirement and technique of these were being reviewed in this section. Regarding to this, the valuable previous studies related to metal, binders, feedstock characterization and much more, are used as a guideline to conduct the present research successfully.

2.2 Powder and binder system

In MIM, there are various types of metal powder were used by researchers; i.e. Stainless Steel 316L, titanium alloy, tungsten carbide cobalt, high speed steels and such on. The appropriate metal powder selection was done by considering their main interest research either for producing the manufacturing products, biomedical applications and such on.

Fundamentally, the powder can be classified into two categories; i.e., water and gas atomized [2,4]. Table 2.1 represents the advantages and disadvantages of both categories. It was stated that the water atomized was produced in irregular shape and the gas atomized was existed in spherical shape. To be highlighted that MIM parts
produced by water atomized particles was able to attain high brown strength that desirable in handling it’s sintering. In fact, it was due to the irregular particles cannot flow past each other’s. However, water atomized powder has the low tap density. This was resulting in high sintering shrinkage as well as the tendency of the irregular particles to slightly align during injection molding. This phenomenon tend to cause a high potential for anisotropic shrinkage to occur. Thus, this is a main reason of why the vendors that using water atomized powder was firstly conducting a milling process which purpose to produce a less irregular and slightly rounded powder. Whereas, the gas atomized have the higher packing density compared to water atomized particle. This will lead to requirement of less binder for injection molding and encouraging the low shrinkage and avoiding distortion during sintering. Also, the spherical morphology of this powder guarantees a more isotropic shrinkage as the particles cannot take a preferred direction during injection molding. Beyond, the disadvantages of this kind of powder are its higher price and lower brown strength.

Table 2.1: Descriptions of water and gas atomized SS316L

<table>
<thead>
<tr>
<th>Types of powder</th>
<th>Water atomised</th>
<th>Gas atomised</th>
</tr>
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<tbody>
<tr>
<td>Microstructure</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Particle shape</td>
<td>Irregular</td>
<td>Spherical</td>
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</table>
| Advantage(s)    | -Promoting excellent moldability  
                  -Lower price  
                  -Improve shape retention during debinding and sintering  
                  -Brown strength is fairly high  | -Higher packing density (needs less binder)  
                  -Spherical morphology guarantee a more isotropic shrinkage  
                  -Low shrinkage and distortion during sintering |
| Disadvantage(s) | -Finer particle sizes have a tendency to agglomerate into effectively larger particles  
                  -Low tap density (resulting in high sintering shrinkage)  
                  -Larger surface area (contributing to a low critical powder loading)  
                  -Lower sintered density  | -Higher price  
                  -Low brown strength (any handling or vibration can destroy the brown part)  
                  -Smaller surface area (contributing to a high critical powder loading) |
| Ref.            | 2,4,13,21      |              |
Previous works shows that the melting temperature of water atomised SS316L which valued by 1371 °C to 1440 °C [21-26]. While, Barreiros et al. highlighted the challenges that must be overcome in Stainless Steel injection molding, especially during sintering [27]. The challenges are listed as below:

a. To decrease binder/carbon content in the feedstock.

b. To decrease carbon contamination during debinding and sintering.

c. To avoid the formation of chromium carbide and presence of precipitation-free zones.

d. To avoid grain growth during sintering.

German and Bose claimed that no binder is perfect and thus the binder selection should be crucially considered [7]. Hence, the selection of suitable binder is a prerequisite in producing a good quality of MIM parts successfully. The binder plays an important role as a temporary vehicle for homogeneously packing a powder into a desired shape and it is functioned to retain the shape until the beginning of sintering process [2]. The binder is usually designed as multi-component system [13]. Asmawi et al. was classified the binders into two groups [12]. The first group is the wax/polymer compounds, while another group is the binder that based on the polymer/polymer compounds. Each of the components of wax and polymer functioned specifically. The polymer functioned to impart rigidity to the part when cold, while the wax works in reducing feedstock viscosity.

Also, Vielma et al. claimed that the binder system is usually designed as multi-component system [13]. The first component is functioned as a backbone binder. It was usually a thermoplastic that supports and maintains the part shape during all phases prior to the later stages of debinding. While the second component, being commonly a wax that improves the feedstock flow ability and it is removed in the early stages of debinding. During debinding, the open pores created allows the gaseous products that produced by remaining polymer to diffuse out from the part. Else, additive act as a surfactant serving as a bridge between binder and polymer can be added.

There are several backbones binder; i.e., polyethylene (PE), polystyrene (PL), ethylene vinyl acetate (EVA), polypropylene (PP), polyethylene glycol (PEG), polymethyl methacrylate (PMMA) among others. Meanwhile, Huang and Hsu claimed that the backbone polymer strongly affects the dimensions and the mechanical
properties of the sintered part [17]. Also, previous study recommended a proper selection of backbone binder, such as HDPE, is required to increase the dimensional accuracy and quality of SS316L sintered parts.

Then, the wetting agent or wax was functioned to improve material flow ability without sacrificing ease of removing it during debinding process. This binder is firstly remove via solvent debinding, leaving open pores that allowed the gaseous products of remaining polymer to diffuse out of the structure [28]. While, Vielma et al. reported that wax binder often exhibit the powder-binder separation, poor strength and a high potential of distortion during the debinding process [13]. This report was made as a precious guideline as not using the wax as a binder system.

Sometimes, it is require to adding up additive (surfactant) which often used is stearic acid [2,13,28,30]. Details on the surfactant are summarized as below:

a. Serving as a bridge between the binder and powder (act as lubricant).
b. Reducing the friction between powder and machine/die walls.
c. Improve dispersion of powder in binder (enhance miscibility between binder components).
d. Enhance powder loading and green strength without sacrificing the flow properties of the mixtures.
e. Giving a better homogeneity.
f. Reduces the contact angle by lowering the surface energy of binder-powder interface minimizing the separation of the binder from the powder-binder mixtures during injection molding.
g. Normally, it is present in a low melting temperature and affinity to preferentially adsorb onto powder surfaces, forming a densely thin outer layer on a particle surface which leads to a more homogeneous packing structure.

Next, German and Bose summarized the ideal binder attributes to flow characteristics, powder interaction, debinding process and manufacturing [7]. It is well presented in Figure 2.1. Previous author affirmed that the appropriate binder selection should considered the all requirements in order to conduct a successful MIM technology. They are claiming that the well-defined facts are consistent with another previous works.
### Flow characteristic
- Viscosity below 10 Pa.s at the molding temperature
- Low viscosity change with temperature during molding
- Rapid change in viscosity during cooling
- Strong and rigid after cooling
- Small molecule to fit between particles and avoid orientation during flow
- Minimum flow orientation

### Powder interaction
- Low contact angle
- Adherence to powder
- Chemically passive, even under high shear and at high temperatures
- Thermally stable during mixing and molding

### Debinding
- Multiple components with differing characteristics
- Noncorrosive, nontoxic decomposition product
- Low ash content, low metallic content
- Decomposition temperature above molding and mixing temperatures
- Decomposition before sintering temperature
- Complete removal as the powder attains structural rigidity

### Manufacturing
- Inexpensive and available
- Safe and environmentally acceptable
- Long shelf life, low water absorption, no volatile components
- Not degraded by cycling heating (reusable)
- High lubricity
- High strength and stiffness
- High thermal conductivity
- Low thermal expansion coefficient
- Soluble in common solvents
- Short chain length, no orientation

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**Figure 2.1:** Ideal binder attributes that concluded by German and Bose [7]

Meanwhile, Arifin et al. reported that a good binder system should be easy to remove in initial removal stage which usually performed by solvent debinding [31]. Where else, the remaining binder remove using next secondary debinding, so called thermal debinding. In this stage, the backbone binder was removed through the pore channels that facilitate by the primary debinding stage. Other than that’s, the ideal binder for MIM should also have the decomposition temperature above mixing and injection molding temperature. Also, it must be lower than the sintering temperature.

Vielma et al. and Patil et al. present some specific requirement for a good binder. First, the binder should facilitate the mixing as well as the injection molding [13,32]. Then, the binder should exhibit the low viscosity at injection temperature, rigid and strong after cooling. Other than that’s, the decomposition product should be non-corrosive, non-toxic and have low ash and metallic contents. Also, it required to have the high lubricity, long shelf life, high thermal conductivity and low thermal expansion. In manufacturing view, the binder must be inexpensive and environmentally friendly.

Else, Wen et al. stated that the binder should [33]:

a. Have a low melting temperature and quickly solidify.

b. Have sufficient strength at room temperature (≥4 MPa), a low viscosity (≤10 Pa.s) and a good fluidity at injection temperature.

c. Being chemically passive and having the ability to wet the particle with a low contact angle (<5 °) and ideally adhere to the particle surface.
d. Being easily remove after shaping and ideally not leaving any residue that potentially causes contamination. The decomposed by products should be non-corrosive and non-toxic.

e. Being commercially available and practically affordable.

Basically, the binder systems constituents for injection moulding application can be divide into two categorize, which are comprised of [31]:

a. Low molecular weight polymer: has low temperature decomposition.

b. High molecular weight polymer: has relatively high temperature decomposition.

Previous study by Vielma et al. applying the virgin HDPE and paraffin wax as a binder system for the manufacturing of bronze and M2 high speed steels parts [13]. Previous author highlighted that HDPE was commonly used as a binder for powder and plastic injection molding. It was found that having HDPE as a binder was able to give various advantages and they are listed as below:

a. Able to produce a good feedstock homogeneity.

b. Able to achieve a suitable rheological behaviour which promotes the easy moldability.

c. The crystalline feature of the HDPE make it perform a good mechanical strength of the part.

d. In advances, the crystallinity feature of the HDPE is able to avoid defects such as swelling, bubble and such on.

Else, Patil et al. have been reported that HDPE was a good secondary binder components since that it can produce the high strength part and able to serve as a backbone polymers during debinding [32].

While, Huang and Tsu studied the effect of different backbone polymer, which are High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE), on the properties of Stainless Steel 316L MIM parts [17]. Previous authors confirmed that the better use of HDPE rather than LDPE. There are 5 conclusions drawn from this previous work:

a. The use of an LDPE as backbone polymer results in a favourable flow behaviour that able to enhance green part’s surface quality.
b. The LDPE/HDPE backbone polymer helps to eliminate the crack defect from sintered part.

c. The use of an HDPE backbone polymer was able to stabilize the spiral flow. This achievement promotes the improvement on dimensions, density, and hardness stabilities of the sintered parts.

d. HDPE backbone binder provides better dimensional stability than does LDPE.

e. HDPE backbone polymer improves the stability of density by 30% and the hardness by 64%.

Ibrahim et al. used Polyethylene Glycol (PEG), Polymethyl Methacrylate (PMMA) and stearic acid (SA) as a binder system for water atomized SS316L metal injection molding [34]. It was highlighted that the PEG and PMMA are highly preferable due to its ability to be easily removed through water leaching and thermal debinding. Moreover, the removing of PEG was only required water as the solution to extract it. This effort was considered as a delicate effort since it was promoting the low cost of debinding. While, SA was added to improve the binder properties such as surface wetting, spreading, adsorption, and binder strengthening. Often, the surfactant was often added as an additive that consists of a functional group adhering to the powder surface and an oriented molecular chain extending into the binder. Also, other researchers such as Amin et al., Jamaludin et al., Sulong et al., Chua et al., Chen et al., Rosip et al. and Rajabi et al. used this established binder system regarding the beneficial facts mentioned above [24,35-40].

It is differ with Supriadi et al. which are investigating the three types of binder system which comprised of Ethylene Vinyl Acetate (EVA) based, polypropylene (PP) based and wax-based system [41]. The wax-based are consisting of paraffin wax, bee’s wax and carnauba wax. It was found that the wax-based binder system achieved the lowest viscosity and heat capacity as well as greater pseudo plasticity than other binder systems. Also, the feedstock which was mixed with wax-based binder system performed the smallest deformation. This result inferred that wax-based binder system was appropriate as binder materials for very fine metal powder applied in MIM.

Conversely, some of the researches are trying to manipulate the potential of environmental substances for being added as a binder for green MIM. For examples are palm kernel, palm stearin, carnauba wax and beeswax [1]. All of these are affirmed
as an environmental friendly binder components and available resource in Malaysia. Instead of that, others are trying to use water soluble binder like PEG where the first stage of debinding was performed using the water leaching.

While, another work of Ibrahim et al. used recycle binder of restaurant waste fat and oil (RWFO) as a binder system of water atomized SS316L [42]. RWFO extracted from the grease traps have been long analyzed as a potential feedstock for biodiesel due to its numerous amounts of fatty acids.

Asmawi et al. applied 60 wt. % waste polystyrene (PS) and 40 wt. % palm kernel oil (PKO) which well blended with 60 vol. % of water atomized SS316L to produce feedstock for MIM [14]. It was found that the feedstock shows a good homogeneity, which was proven by conducting several tests; i.e., feedstock density, binder burn-out, rheology and Scanning Electron Micrograph (SEM) observation.

Omar and Subuki applied 50/60/70 wt. % of palm stearin (PS) and 50/40/30 wt. % of polypropylene (PP) as a binder system to be mixed with 65 vol. % gas atomized SS316L [3]. These authors claimed that the higher PS content provided the better sintered part’s density.

Nor et al. applied palm stearin as the binder system in MIM and the study of characterization of the feedstock was conducted [2]. In previous study, Titanium alloy was mixed with 60 wt. % of palm stearin and 40 wt. % of polyethylene [35]. Palm stearin has been reported that having a good attribute as a binder system in MIM [2,43]. Since it was an available resource in Malaysia, palm stearin has been a potential binder system that can be applied in MIM. Moreover, it was consist of fatty acid which functioned as a surface active agent for many binders that are used [2]. Instead of that, the major benefit of the palm stearin is on the ability of modifications that can be done on its chemistry and rheological properties in order to meet the specific requirement of MIM.

Meanwhile, Asmawi et al. produced feedstock that consist of 60 vol. % SS316L, 60 wt. % of waste polystyrene and 40 wt. % of palm kernel [12]. It has been reported that the waste polystyrene give a major threat to the environment because this typical plastics are non-biodegradable. Thus, its disposal in landfills is limited due to high cost of the incineration and space. Therefore, the major constraint of applying the waste polystyrene is about the wettability and particle bonding between metal powder and waste polystyrene. Previous author was stressed out several problem of applying the waste polystyrene which are the moldability performance, compatibility
issue and its diffusion during thermal degradation as it contains hydrocarbon chain with a phenyl group attached to every other carbon atom.

2.3 Mixing

Mixing is a process where all materials are mixed in purpose to produce homogeneous feedstock. The materials include are consist of the metal powder, primary binder and secondary binder or else the surfactant if necessary, which is depend on the binder system that applied. Knowing the deficiencies in quality of the feedstock cannot be corrected by subsequent processing modification, the feedstock preparation was being the most crucial process in MIM technology. Consequently, it is essential to mix the selected powders and binder in correct composition and technique [44]. So that, the homogeneous feedstock with free of powder-binder separation or particle segregation was able to be obtained. However, failure in dispersing powder uniformly in the binder and unsuitable rheological behaviour of feedstock will cause molding defects such as distortion, cracks, or voids that will lead to non-uniform shrinkage or warping in the sintered parts.

Prior study by Supati et al. discovered that there are several parameters such as time, temperature, sequence of material addition, powder size and shape, formulation of binder, shear rate, and powder loading that must be considered for producing good homogeneity of feedstock [44]. In that sense, they was establish the suitable mixing parameters for the research which are consisting of mixing temperature, speed and powder loading, while the other parameters are kept constantly. It was to be highlighted that the appropriate volumetric powder loading and best mixing conditions are essential to determine the former in order to obtain a moldable feedstock since powder loading controls the net dimensional shrinkage and influences the final part quality.

Else, German and Bose mentioned that it was need to focus on three things in evaluating the feedstock [7]. The terms are solids loading, critical solid loading and optimal solid loading. Displayed in Table 2.2 was the description of all terms. Noted that the best powder loading could minimised the distortion, defects and shrinkage of the injected part [45].
Table 2.2: Details of solid loading, critical solids loading and optimal solids loading

<table>
<thead>
<tr>
<th>Item</th>
<th>Solids loading</th>
<th>Critical solid loading</th>
<th>Optimal solid loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>Volumetric ratio of solid powder to total volume of the powder and binder [29].</td>
<td>Composition where the particles are tightly packed together, without external pressure and all space between the particles is filled with binders [2,43,46].</td>
<td>Point where the feedstock sufficiently having low viscosity for molding but exhibits good particle-particle contact to ensure shape preservation during processing [43].</td>
</tr>
</tbody>
</table>
| Description | Often expressed on a volume percentage basis (value near 60% for PIM) [29].     | Crucial in determining the range of an appropriate powder loading of a specific metal powder [2,43,46]. | -Less powder than the critical solids loading.  
-Estimated based on the critical powder loading [43]. |

Moreover, German and Bose highlighted that the optimum powder loading should be kept approximately 2% to 5% lower than critical loading [7]. This was also supported by Nor et al. and Amin et al. which applying this principle while fixing optimum powder loading in their studies [2,43].

Previous work by Benson et al. reported that the higher powder loading was resulting in a better shape retention. Also, this type of powder loading tend to enhance sintering part, specifically in minimizing sintered part’s shrinkage [47]. However, beyond on the certain powder volume percent, the possibility for producing inhomogeneous feedstock was higher compared to lower powder loading due to the difficulties in mixing process. Other than that’s, the high feedstock viscosity would make it unsuitable for injection molding. However, for the low powder loading, it may result in powder-binder separation under high pressure during molding, and may cause difficulties in obtaining the near full of theoretical density. Thus, it was recommended to keep maximum powder loading while keeping the feedstock viscosity as low as possible.

Whereby, previous work by Amin et al. found that the critical powder loading was a vital factor in order to determine rheological properties and inter-particle distance [43]. Also, it was mentioned that the critical powder loading may influences by several powder characteristics; i.e., mean size (coarse or fine), particle shape (spherical or irregular), and particle size distribution (wide, narrow, monomodal or bimodal) and by the binder system.

Else, a thorough study by Patil et al. claimed that the fineness was the essential requirement of the powder [32]. It was mentioned that the mean particle size should be less than 30 microns for the MIM technology. Consequent of the achievable
fineness, the size distribution should encourage the packing of the powder necessarily. The particle surfaces also should be clean in order to prevent powder agglomeration. Also, Jamaludin et al. stated that the fine powder performed a better densification than the coarse powder, and it was due to the larger surface exhibit in the powder itself [21].

Another concern was related to the molecular weight of the binders. Subuki et al. applied a greater molecular weight of polypropylene (PP), polyethylene (PE), thermoplastic natural rubber (TPNR) as the backbone polymer due to the high contribution towards strength characteristic especially during thermal debinding [30]. Meanwhile, Paraffin wax (PW) and palm stearin (PS) were used as the primary binder system due to their low melting point and viscosity.

Next, the mixing technique is able to affect feedstock’s homogeneity [28]. Thus, Table 2.3 shows the mixing technique that was applied by previous researchers. It was built according to several properties; i.e., type of metal powder, powder loading, feedstock composition, type of mixer, mixing speed, mixing temperature and the mixing duration. Details in this was discussed as below.

There are several types of machine that are commonly used; i.e., roll mills, high-shear mixers, shear rolls and screw extruders [16,28]. The first two are examples of batch operation’s machine, while the last two are suitable for continuous operation. The machine selection was depending on the details application and materials to be used for feedstock preparation. For examples, a very fine particles which highly probability of agglomeration is requiring the planetary or z-blade mixers. This type of particles need a longer mixing duration instead of not using the preferable mixing machine. While, it was recommended the use of the twin-screw extruders or shear rolls for high volume productions. Thus, it was beneficial for researchers to know the capability and capacity of their mixer to ensure the successful of producing the good feedstock homogeneity.

Here was some valuable information that can be summarized accordingly to Table 2.3:

a. The mixing temperature was fixed in range temperature of the highest melting temperature and the lowest degradation temperature [7].

b. By referring the highest melting temperature of the binders, the mixing temperature was fixed by adding up about 3.16 °C to 38.50 °C.

c. So, it was suggested to the researchers to adding up the aforementioned range in purpose to conduct a successfully mixing.
Supati et al. claimed that the shear rate was controlled by speed of the mixing blades [44]. Increase of mixing speed promotes increase of feedstock homogeneity. The temperature rise due to the amount of energy input by mixer blades was converted to heat during shearing of the mixer increase with increase of speed. This was particularly detrimental to low melting point binder constituents, if any. Again highlighted, the mixing temperature should be in the range of lowest degradation temperature and the highest melting temperature of the binders [2,13,43]. A higher mixing temperature is required to enhance the deagglomeration process that cause by the higher binder viscosity [44]. Nevertheless, too high mixing temperature will cause the powder-binder separation and heterogeneous feedstock are produce. Ibrahim et al. works on the water atomized SS316L powder for micro metal injection molding which focusing on the rheological optimization [48]. As known a good mixing technique was too important for ensuring the good homogeneity and flow ability of the molten feedstock during mixing and injection molding process. Thus, previous study highlighted the mixing technique that was applied. It was presented in Figure 2.2 below.

Mix SS316L with SA for 5 min at room temperature

Mix both mixture for 15 minutes at room temperature

Adding up PEG and mix for 15 minutes at room temperature

Mix the all materials at 70 °C within 1 hour

Binder composition:
- 73 % Polyethylene Glycol (PEG)
- 25 % Polymethyl Methacrilate (PMMA)
- 2 % Stearic Acid (SA)

Figure 2.2: Mixing technique used by Ibrahim et al. [48]
Table 2.3: Trend of mixing temperature applied in MIM

<table>
<thead>
<tr>
<th>Metal powder</th>
<th>Powder loading (vol. %)</th>
<th>Binder system</th>
<th>Melting temperature (°C)</th>
<th>Degradation temperature (°C)</th>
<th>Density (g/cm³)</th>
<th>Item(s)</th>
<th>Machine</th>
<th>Speed (rpm)</th>
<th>Duration (minutes)</th>
<th>Year</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina</td>
<td>58</td>
<td>HDPE</td>
<td>129.78</td>
<td>Start/end (470/550)</td>
<td>0.96</td>
<td>140.00</td>
<td>Haake Rheocord 252p</td>
<td>40</td>
<td>30</td>
<td>2008</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PW</td>
<td>56.97</td>
<td>Start/end (200/400)</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA</td>
<td>71.05</td>
<td>Start/end (200/400)</td>
<td>0.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS316L</td>
<td>63,65,67, 69</td>
<td>PS</td>
<td>61.00</td>
<td>Start/end (288/463)</td>
<td>-</td>
<td>150.00</td>
<td>Sigma blade</td>
<td>50</td>
<td>120</td>
<td>2009</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PE</td>
<td>127.00</td>
<td>Start/end (390/502)</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS316L</td>
<td>-</td>
<td>LLDPE</td>
<td>130.00</td>
<td>-</td>
<td>0.92</td>
<td>135.00</td>
<td>Brabender Plastograph EC (rotary mixer)</td>
<td>25</td>
<td>60</td>
<td>2011</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PS</td>
<td>61.31</td>
<td>-</td>
<td>0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA</td>
<td>69.60</td>
<td>-</td>
<td>0.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZK60 Magnesium Alloy</td>
<td>64</td>
<td>PS</td>
<td>52.00</td>
<td>Start/end (288/463)</td>
<td>0.89</td>
<td>150.00</td>
<td>Sigma blade</td>
<td>-</td>
<td>60</td>
<td>2012</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LDPE</td>
<td>130.00</td>
<td>Start/end (389/501)</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC-Co</td>
<td>61</td>
<td>PS</td>
<td>61.42</td>
<td>Start/end (398.5/598.8)</td>
<td>-</td>
<td>130.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2014</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PE</td>
<td>126.84</td>
<td>Start/end (389.6/501.6)</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SS316L</td>
<td>60</td>
<td>PS</td>
<td>185.00</td>
<td>-</td>
<td>0.91</td>
<td>190.00</td>
<td>Brabender Plastograph EC (rotary mixer)</td>
<td>30</td>
<td>60</td>
<td>2014</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PKO</td>
<td>30.00</td>
<td>-</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS316L</td>
<td>60</td>
<td>PP</td>
<td>170.00</td>
<td>-</td>
<td>-</td>
<td>175.00</td>
<td>Brabender Plastograph EC (rotary mixer)</td>
<td>30</td>
<td>60</td>
<td>2014</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SF</td>
<td>60.00</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Processing Time</td>
<td>Temperature</td>
<td>190.00</td>
<td>50</td>
<td>120</td>
<td>2014</td>
<td>30</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SS316L</td>
<td>65</td>
<td>PS</td>
<td>61.60</td>
<td>470.40</td>
<td>-</td>
<td>190.00</td>
<td>Brabender Plasticorder</td>
<td>50</td>
<td>120</td>
<td>2014</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PE</td>
<td>125.50</td>
<td>502.60</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PP</td>
<td>171.10</td>
<td>486.60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PW</td>
<td>59.80</td>
<td>498.60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TPNR</td>
<td>121.60</td>
<td>362.20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SS316L</td>
<td></td>
<td>Palm kernel oil</td>
<td>30.00</td>
<td>363.40</td>
<td>0.91</td>
<td>190.00</td>
<td>Brabender Plastograph EC (rotary mixer)</td>
<td>30</td>
<td>60</td>
<td>2016</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waste polystyrene</td>
<td>185.40</td>
<td>324.30</td>
<td>1.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SS316L</td>
<td>63</td>
<td>PS</td>
<td>70.00</td>
<td>-</td>
<td>0.89</td>
<td>150.00</td>
<td>Brabender Plastograph EC (rotary mixer)</td>
<td>-</td>
<td>-</td>
<td>2017</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LDPE</td>
<td>111.50</td>
<td>-</td>
<td>0.92</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Whereas, Asmawi et al. mixed 60 vol. % Stainless Steel 316L with 60 wt. % of waste polystyrene and 40 wt. % of palm kernel oil [12]. The materials are mixed at 190°C with the rotational speed of 30 rpm using Brabender Plastograph EC within 1 hour. It is worth to know that the mixing temperature of 190 °C was selected in order to prevent the binder constituent from degrade since it was within the highest melting temperature (185 °C) and the lowest degradation temperature of the binder system (324 °C). The waste polystyrene and palm kernel oil are fully melted at this temperature. The mixing was started by adding up the waste polystyrene and mix it for 10 minutes. Next, the metal powder was added and followed by palm kernel oil, and they are mixed for 60 minutes. Later, the blended feedstock was taken out from the mixer and leave to cool at room temperature before being crushed into small pallet using Granulator machine.

Then, previous study by Subuki et al. mixed 65 vol. % SS316L with various type of binder and composition [30]. Three different binder systems are prepared; i.e., feedstock A (70 % PS/30 % PE), feedstock B (70 % PS/30 % PP), feedstock C (40 % TPNR/60 % PW). Owing to greater molecular weight, PP, PE and TPNR are selected as the backbone polymer. It was expected that this binder system was able to attain a high strength part especially during thermal debinding. While the PW and PS are used as the primary binder and the major fraction in binder system due to their low viscosity and melting point. The mixing was conducted by using Brabender Plasticorder at 190 °C for about 2 hours with a rotational speed of 50 rpm. First, a quarter amount of polymer is loaded into the mixer bowl. Then, the powder was loaded gradually together with the remaining binder. The homogenous feedstock was assumed to be produced regarding to the mixing torque yielded a stable and consistent value.

Also, a thorough knowledge of the material properties of the developed binder system and feedstock are essential for successful of the powder injection molding (PIM) [8]. In view of the above, characterization of a developed binder system and feedstock has been reported as a compulsory process. It is supported by Subuki et al. which claimed that the powder, binders and feedstock characterization was one of the most important steps in metal injection molding technology because the subsequent processes (molding, debinding, and sintering) were depend on the properties of the binders and feedstock [30]. It have been too crucial because the part defects cannot be controlled in the subsequent processing steps [43]. So, the all steps involved in
characterisation of feedstock is needed to be monitored since they will affect the final product [2,53].

Nor et al. stated that the metal powder and binder’s characterization are being the crucial step in purpose to understand the whole process of MIM [2]. Aforementioned, the initial properties of the feedstock will dictate the final properties of the sintered part. Then, there are some characterization tests that have been conducted in this study. There are density test, scanning electron microscopy (SEM), critical powder volume percentage (CPVP), energy dispersive X-ray diffraction (XRD), thermo gravimetric analysis (TGA) and differential scanning calorimetry (DSC).

While, Amin et al. studied the potential used of sewage fat as binder in MIM technology [1]. The sewage fat (SF) is also called as fat oil grease (FOG). The previous study found that the binder formulation of 40/60 (SF/PP) was the best binder composition according to homoogeneity and rheological test.

According to Amin et al., the cemented carbide (WC-Co) was mixed at an optimal powder loading (within 2 % to 5 % lower than CPVP value which is 65 %) with 60 % palm stearin and 40 % polyethylene [43]. It has been reported that the optimal powder loading of the powder was valued by 61 %. The result was based on rheological characterization that has been conducted. It was consisted of several properties, i.e., pseudoplastic behaviour, powder law index (n) lower than 1, low activation energy and highly moldability index.

Whereas, Amin et al. also conducted the study of mixing homogeneity and rheological characterization for optimal binder formulation for metal injection molding of Stainless Steel 316L with two binder formulation of 70/30 and 60/40 between Polypropylene (PP) and Sewage Fat (SF) [1]. The best rheological behaviour are studied according to viscosity, shear rate and powder law index. Thus, the test shows that the both formulations are exhibited pseudoplastic behaviour. After homogeneity test and rheological test, it show that the sewage fat has shown a great potential for being used as the major binder component for MIM process. Previous author found that 60/40 (PP/SF) was exhibit the ideal binder composition according on rheological analysis and mixing homogeneity.

Other than that’s, Vielma et al. conducted the homogeneity test using three methods [13]. First, the torque value was applied to measure the resistance of rotor blades. Probably, when a steady state of the torque reached, it can be said that the
uniform mixing of the feedstock was achieved and leads in producing the good feedstock homogeneity. Next, the density for three crushed feedstock of the same batch of mixing session are measured. The small deviation from the mean density indicates the good feedstock’s homogeneity. Third, the capillary rheometer was used. The pressure fluctuation was being studied through a small capillary while keeping the shear rate as a constant. They stated that the small variation of testing time and capillary pressure indicates the homogeneous feedstock, whereby the high fluctuations indicates heterogeneous distribution of power in the binder. Details stated are when the minimum and maximum pressure represent binder rich and solid-rich feedstock portions, respectively.

2.4 Rheological characterization

Generally, the rheological characterization was conducted to investigate the rheological behavior existed in a flow material. Previous work by Agote et al., Nor et al., Ibrahim et al. and others claimed that the pseudoplastic/shear thinning behavior was required in MIM technology [2,9,34]. Technically, the pseudoplastic exhibit when the viscosity was decrease as the increase of shear rate. At the meantime, the viscosity must be in range of 10 Pa.s to 1000 Pa.s [13,54-56]. Else, the rheological behavior of dilatant was extremely avoided in MIM [45,54]. This undesired behavior could be indicate when the viscosity is increase with the shear rate. Noted that the existing of this undesirable behavior was indicating the powder binder separation occurred during the flow of molten feedstock.

While, Ibrahim et al. claimed that it was desired in MIM for the viscosity should decreased fast with the increase of shear rate during injection molding [54]. The high shear sensitivity is important to produce a complex, delicate and miniaturized parts. Also, they found that the lower value of E stated that any small fluctuation of temperature during molding will not result in sudden viscosity change. Noted that a sudden change could cause undue stress concentrations in molded parts, resulting in cracking and distortion. Table 2.4 summarized the rheological characteristic which desired in MIM.
Table 2.4: Summary of rheological characteristic

<table>
<thead>
<tr>
<th>Item(s)</th>
<th>Symbol</th>
<th>Unit</th>
<th>Requirement</th>
<th>Description(s)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow behaviour exponent</td>
<td>n</td>
<td>-</td>
<td>Lower</td>
<td>- Indicates the degree of shear sensitivity</td>
<td>[2,43,49,54]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Lower n, faster the viscosity changes with shear rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Less than 1 (desired for MIM)</td>
<td></td>
</tr>
<tr>
<td>Flow activation energy</td>
<td>E</td>
<td>kJ/mole</td>
<td>Lower</td>
<td>- Expresses effect of temperature on feedstock viscosity</td>
<td>[43,54]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Lower E indicates that the viscosity is not so sensitive to temperature variation</td>
<td></td>
</tr>
<tr>
<td>Rheological index</td>
<td>(\alpha_{stv})</td>
<td>-</td>
<td>Higher</td>
<td>- Demonstrate the quality of the feedstock for injection molding in terms of flowability</td>
<td>[43,54]</td>
</tr>
</tbody>
</table>

2.5 Injection molding

At the injection molding stage, the part is formed into a desired shape, so called by green part, which was produced by applying the specific range of heat and pressure. The feedstock is heated at a temperature above the melting points of binders but below the highest degradation temperature of binders [32]. Noted that, the too high in feedstock viscosity resulting in parts defect during injection molding.

Previous works by Kamaruddin et al. and Chua et al. applied Taguchi Method in order to optimize the injection molding [37,57]. The listed molding parameters that have been included in their studies are nozzle temperature, front temperature, injection pressure, speed, cooling time, holding time, injection time and much more.

Berginc et al. had classified the molding parameters into two categories which are comprised of controlled and uncontrolled parameters [58]. Table 2.5 shows both types of parameter, while displayed in Table 2.6 is the injection molding parameters indication that prepared for briefly elaborates some injection parameters.

Table 2.5: Categories of injection molding parameters [58]

<table>
<thead>
<tr>
<th>Controlled parameters</th>
<th>Uncontrolled parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material temperature</td>
<td>Die shape</td>
</tr>
<tr>
<td>Injection speed</td>
<td>Pressure drop</td>
</tr>
<tr>
<td>Duration of holding pressure</td>
<td>Mold temperature variation</td>
</tr>
<tr>
<td>Holding pressure</td>
<td>Mixture homogeneity</td>
</tr>
<tr>
<td>Cycle time</td>
<td>Material heating due to friction</td>
</tr>
<tr>
<td>Mold temperature</td>
<td>Moisture in the material, etc.</td>
</tr>
</tbody>
</table>
REFERENCES


[61] Ibrahim, M. H. I., Muhamad, N., Sulong, A. B., Jamaludin, K. R. and Nor, N.


[89] Nor, N. H. M., Ismail, M. H., Muhamad, N., Ruzi, M. and Jamaludin, K. R.


