CHARACTERIZATION OF 316L STAINLESS STEEL POWDER INJECTION MOLDING

by

Nadiatul Haswin bte. Hassan Merican

A project dissertation submitted to the

Mechanical Engineering Programme

Universiti Teknologi PETRONAS

In partial fulfillment of the requirement for the

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(MECHANICAL ENGINEERING)

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Universiti Teknologi PETRONAS

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Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

_____

(AP Dr. Faiz Ahmad)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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NADIATUL HASWIN BTE. HASSAN MERICAN

ABSTRACT

This report presents the research that had been conducted during current semester and progress on the project so far based on this chosen topic, which is Characterization Of 316L Stainless Steel Powder Injection Molding. The objective of the project is to find the optimum parameters for powder injection molding of 316L Stainless Steel.

In this project, metal powder and the binder characterization were carried out. The suitable binder system proportion, formulation of mixture of powder and binder were determined and the powder and the binder were mixed. The feedstocks then were characterized by using rheometer and Thermal Gravimetrical Analyzer (TGA). The results shows that the rheological behavior of both formulations of the feedstocks are suitable for injection molding.

The samples were injection molded without physical defects. Molded sample will go through debinding process to remove the binder and keep its shape. The debinding process consists of two sub-processes; solvent extraction and thermal debinding. For solvent extraction, the optimum temperature and time is 60^{o}C for 5 hours respectively. For thermal debinding process, the samples are successfully debond with the best heating rate, 7^{o}C/min, to temperature of 450^{o}C for 1 hour dwell time.

ACKNOWLEDGEMENT

First and foremost, I would like to express my praises to ALLAH for His blessing.

My deepest appreciation and gratitude is extended to my supervisor, AP Dr. Faiz Ahmad for all his teachings, guidance, supervision and supports from the preliminary to the final report enable me to develop an understanding of the subject. It has been a hardship for you, sorry and thank you so much.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Injection molding is considered one of the most common plastic part manufacturing processes. The process usually begins with taking the polymers in the form of pellets or granules and heating them to the molten state. The melt is then injected or forced into a chamber formed by a split-die mold. The melt remains in the mold and is either chilled down to solidify (thermoplastics) or heated up to cure (thermosets). The mold is then opened and the part is ejected.

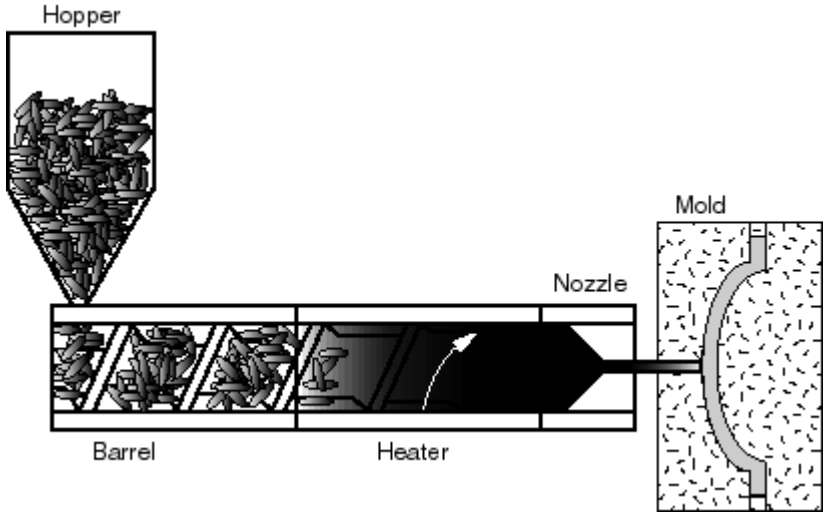

Figure 1: Injection Molding Process

Metal or ceramic can be used with injection molding and it is called powder injection molding (PIM). PIM is a derivative of polymer injection molding and uses much of the same technology, with addition of debinding process and sintering process from powder metallurgy and ceramic processing. In PIM, polymeric binders are pre-mixed with metal or ceramic powders. The mixture is heated in a screw-fed barrel and forced under pressure into a die cavity, where it cools and is subsequently ejected. The

polymer is then removed and the component sintered. The process flow is shown in Figure 2.

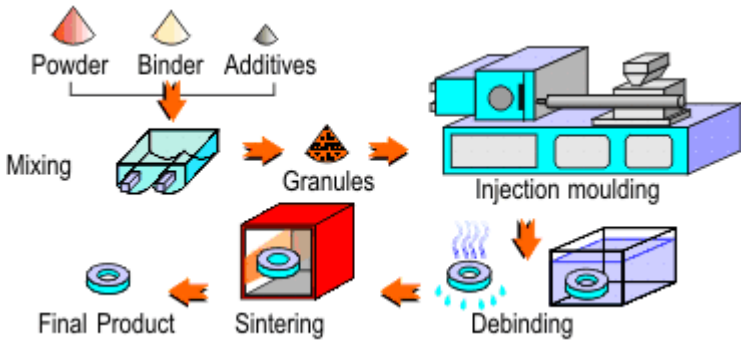

Figure 2: Powder Injection Molding Process [2]

Stainless steel Type 316 is an austenitic chromium-nickel stainless steel containing molybdenum. Type 316L is an extra-low carbon version of Type 316. It often uses include exhaust manifolds, furnace parts, heat exchangers, jet engine parts, photographic equipment, tubing, parts exposed to marine atmospheres and many more application. [1]

1.2 PROBLEM STATEMENT

Currently, stainless steel is widely used in many applications such as aerospace parts, computer components, high temperature turbines and much more. As the stainless steel needed in various design and complex shapes, powder injection molding is the best answer.

The selection of appropriate powder and binder system, mixing of the powder and the binder system and its viscosity will affect the product. The characterization of the powder, binder system, mixing and rheological needed to be studied for optimum performance of the product.

1.3 OBJECTIVES

The main purpose of this project is to find optimum parameter on powder injection molding of stainless steel 316L for two different formulation. This study will focus on the powder and binder system characterization, feedstock preparation and rheological characterization for injection molding until debinding process.

1.4 SCOPE OF STUDY

This study will involve fabrication of Stainless Steel parts by using Powder Injection Molding. It contains six parts which are powder characterization, binder characterization, feedstock preparation, molding, physical examination, and debinding process. The powder and binder characterization will be carried using Scanning Electron Microscope (SEM) and Thermal Gravity Analyzer (TGA).

1.5 FEASIBILITY OF PROJECT

This project will require some experimental works in producing the molded stainless steel type 316L parts and to study its process characterization and properties of the product. This project can be done within the allocated time given that everything goes fine as planned. All of the objectives can be achieved if the procedures are followed closely.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 POWDER INJECTION MOLDING

Powder injection molding (PIM) is a combination of plastic injection molding and powder metallurgy process currently used for the production of complicated and near-net-shape parts of high performance materials. This technique basically combines the advantages of the plastic injection molding with the versatility of the traditional powder metallurgy, producing highly complex part of small size, tight tolerance, and low production cost. [11]

2.1.1 Advantages

One of its advantages is high production rates [13]. One cycle of the process is less than a minute depends on the material used and the size of the product[12,13]. Its design flexibility is also high, since the mold can be created to make any complex design of product [13]. Since the whole mold is a machine that doesn't require a whole team to operate, so labor fees are relatively low [12]. It also has ability to combine functions and eliminate sub-assemblies [12,13]. It has good dimensional control with close tolerances of ±0.5%[12]. It has no secondary operation as it produce net shape production [4,11-13,17]. It also produces good surface finishes [13].

2.1.2 Disadvantages

There are some disadvantages to use injection molding as our processing method as well. Such as high initial equipment investment, the mold itself will cost around RM30,000 to RM40,000 according to our needs and size [12,17]. The cost of the machine is also relatively high [17]. Therefore, in order to cut back the losses, we only can use this process if the demand is very high (for mass production). Other than that,

the part must be designed properly for effective molding, such as the injection point, the cooling area and much more. The accurate cost prediction for molding is also difficult.

2.2 STAINLESS STEEL 316L

Stainless steels are chromium containing steel alloys . The minimum chromium content of the standardised stainless steels is 10.5%. The Chromium makes the steel "stainless" and this means improved corrosion resistance [1].

Stainless Steel Type 316L is an austenitic Chrominum-Nickel stainless steel with superior corrosion resistance. The low carbon content reduces susceptibility to carbide precipitation during welding [2,6].

Table 1: Chemical Composition of 316L SS [11]

Element	%
C	0.03
Si	0.5
Mn	0.5
P	0.04
S	0.03
Ni	10-11
Cr	16-17.2
Mo	2-2.4
Cu	0.1
N	-

Table 2: Mechanical and Physical Properties of 316L SS [1]

	316L
Ultimate Tensile Strength	558MPa
Yield Strength	290MPa
Hardness Rockwell	B79
Density	7.99g/cm^3

Melting Point (Approx)	$1370^{o}C$

Powder should have size less than 20µm, tap density less than 50% of theoretical density, spherical in shape and free from agglomeration [11]. Sintered density is more important to achieve excellent mechanical properties and good corrosion resistance [11] while sintering temperature and heating rate affect the mechanical properties [11,14]. Using different size powders will increase the packing density [7,11].

2.3 BINDER

The binder systems are usually composed of polymer mixtures and most important on the PIM process. The binder must be low viscosity material to lower viscosity to make it suitable for molding as well as to have extractability by debinding [5]. The role of binder systems is like transporter, which is helpful for the homogeneous distribution of metal powder into the desired shape [11]. These systems also hold the particles in the beginning of sintering process [11].Several binder systems are available but the formulation depends upon the metal powder size, shape and size [11]. Different binder systems is investigated [11] and found the binder system contained 62 wt.% of paraffin wax is an excellent one.

Multi binders are used in this process as each binder has its own role. Polypropylene(PP) or polyethylene(PE) used to keep the component in shape after injection molding process and debinding process [3,9]. Paraffin wax used to decreased the feedstock viscosity and increase replication ability [3,9]. Surfactants such as stearic acids are used in order to improve powder wetting [3,9]. The powder and the binder are mixed together and this mixture is called feedstock. The use of low amounts of binder produces high viscosity feedstock [10-11]. This will make molding process difficult. High amount of binder will result in low strength and may produce heterogeneous green parts [9].

CHAPTER 3
METHODOLOGY

3.1 EXPERIMENTAL METHODOLOGY

The project activities are summarized in Figure 3 below. This process is based on Powder Injection Molding flow chart.

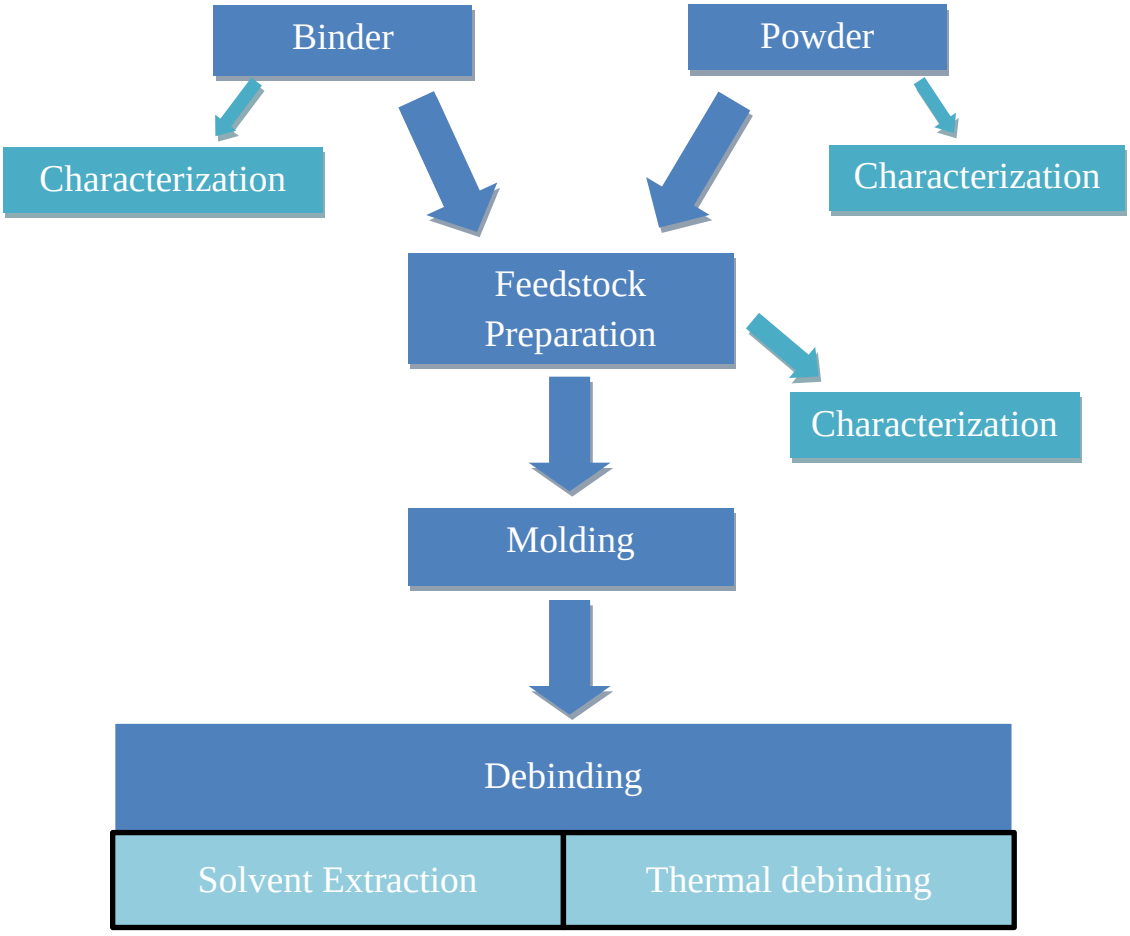

Figure 3: Flow Chart of the Project

3.11 Materials Study

The metal powder used in this study is stainless steel 316L (PF-10R) water atomized supplied by PICIFIC SOWA Japan. The particle shape is observed using Scanning Electron Microscope (SEM). Besides that, the particle size or dimension also can be obtained using SEM.

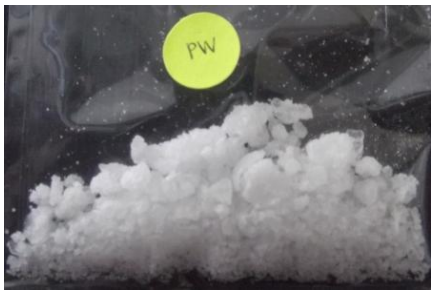

Figure 4: Paraffin Wax (PW)

Figure 5: Polypropylene (PP)

Figure 6: Stearic Acid (SA)

The polymeric based binder system is used to make the easy flow of the metal powder into mold cavity. In this study, Paraffin Wax (PW) based system was used. Polypropylene (PP) and Stearic Acid (SA) are also used to keep the component in shape after injection molding process and solvent debinding process and to improve the powder wetting respectively. The composition of the binder system was PW 70vol%, PP 25vol% and SA 5vol%. The binder system was characterized by using Thermal Gravity Analyzer (TGA).

3.12 Feedstock Preparation

Two formulation are prepared with solid loading 67%vol and 69vol% named F1 and F2 respectively. The mass of the metal powder and binder are determined. The mixing was done and then, the paste was converted to granules. The characterization of the feedstock is done using TGA and capillary rheometer.

3.13 Molding

The feedstock then undergoes injection molding process. The samples were molded at temperature of 175^{o}C at 4.5bar. The molding time differs from 15-20 seconds.

Figure 7: Green samples

(69% formulation on the upper side of the picture and 67% formulation on the bottom side of the picture)

3.14 Physical examination

The molded samples (green parts) are observed if there any defects such as crack, powder-binder separation or voids. In this study, defects free samples were molded. The dimension of each molded parts and mass were recorded.

3.15 Debinding

Debinding process consists of two sub-processes; solvent extraction and thermal debinding. These processes are carried out to remove the binder from the green parts.

Solvent extraction process removes the PW, the soluble component of the binder. In this study, the green parts are immersed in n-heptane at 60^{o}C as the highest temperature leads to the highest extraction rate and too high temperature could form cracks in the green molded body after the extraction. The debinding ratio was measured [10].

Thermal debinding process is carried out after the solvent debinding process. The speciments were heated at 450^{o}C for dwell time 1 hour with different heating rates (3^{o}C/min, 5^{o}C/min, 7^{o}C/min and 10^{o}C/min) to optimize the suitable debinding rate.

3.2 Project Gantt Chart

Table 3: Gantt Chart

Activity	FYP 1				FYP 2				
	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
Early Stage of Documentation									
Studies on Powder Injection Molding and Material.									
Particle size, shape observation. Binder system thermally characterization.									
Mixing & Rheology									
Molding									
Solvent Debinding									
Thermal Debinding									
Report documentation.									

3.3 Project Keymilestone

Table 4: Key Milestones

Activity	FYP 1				FYP 2				
	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
Determine the formulation of the feedstock.									
Completion of feedstock.									
Completion of molding.									
Completion of solvent debinding									
Completion of thermal debinding.									
Conclude The Analyses and report documentation									

3.4 TOOLS AND EQUIPMENTS

In this project, several tools or equipment will be used in order to complete the project.

I. Mixer for feedstock preparation.

II. Capillary rheometer

Figure 8: Capillary rheometer

III. Injection molding machine

Figure 9: Injection molding machine

IV. Circulating Water Bath for Solvent Extraction

Figure 10: Circulating Water Bath

V. Thermal gravimetrical analyzer (TGA)

Figure 11: Thermal gravimetrical analyzer (TGA)

VI. Scanning electron microscopy (SEM)

Figure 12: Scanning Electron Microscopy (SEM)

VII. Tube Furnace

CHAPTER 4
RESULTS & DISCUSSIONS

4.1 SEM ANALYSIS ON METAL POWDER

The metal powder has been observed under Scanning Electron Microscope and the micrograph is shown in Figure 13 and 14.

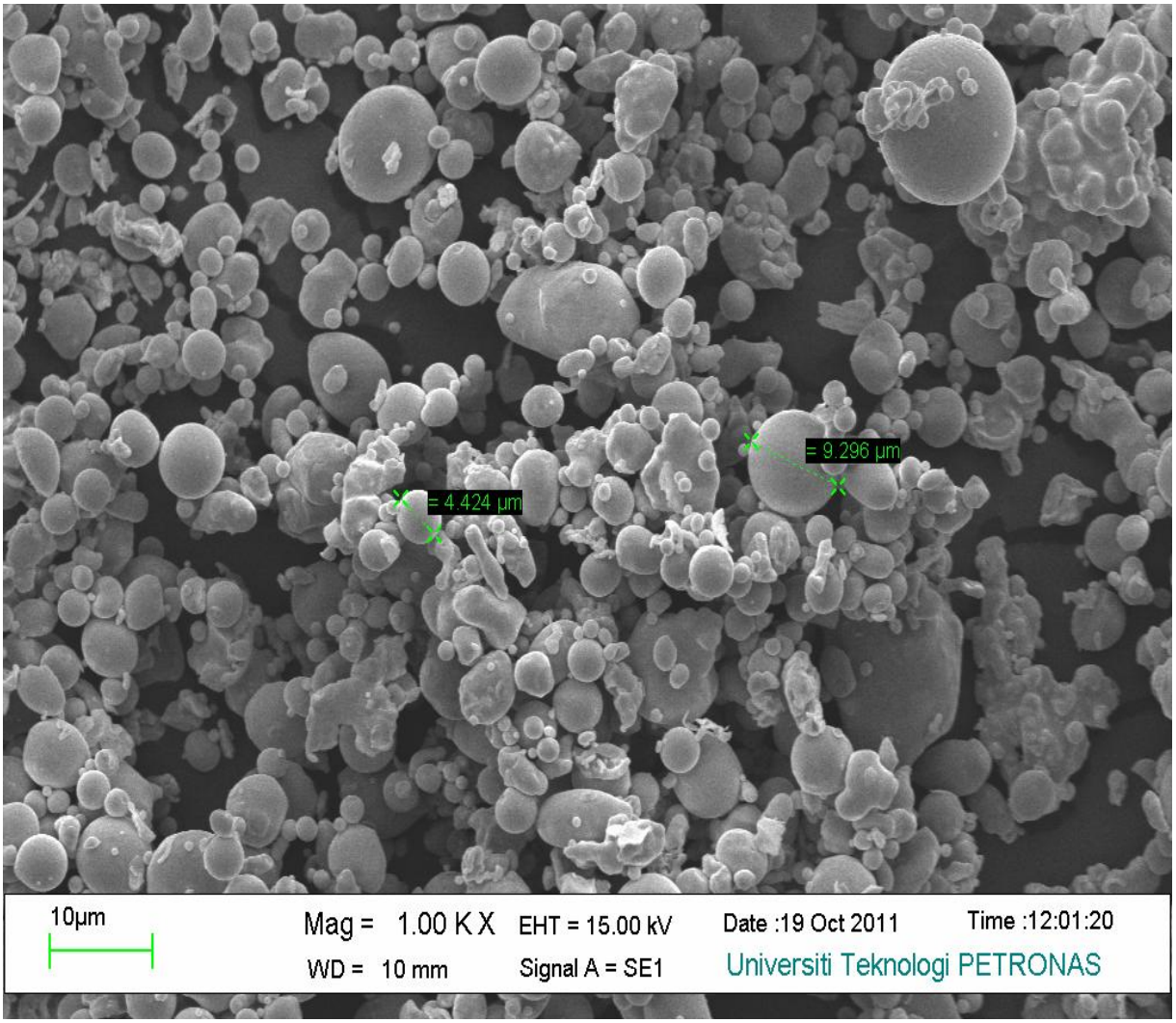

Figure 13: SEM micrograph of 316L SS at 1000X with particle diameter

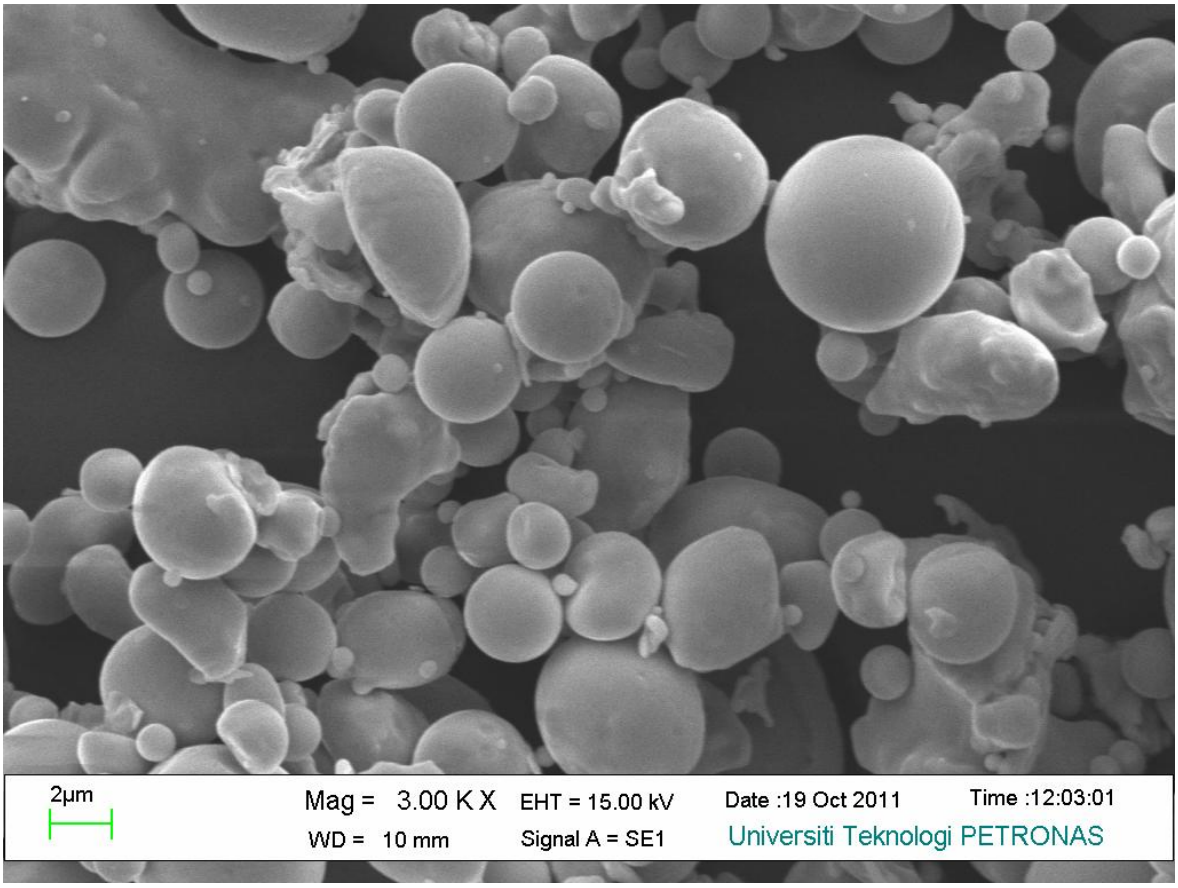

Figure 14: SEM micrograph of 316L SS at 3000X

The powder particles are observed and it is clear that the powder particles have round shape. The metal powder used was stainless steel 316L (PF-10R) water atomized supplied by PICIFIC SOWA Japan. The mean particle size is 5-7µm[11]. The chemical composition of the powder is given in Table 5.

Table 5: Chemical Composition of 316L SS -10PF [11]

Element	%
C	0.024
Si	0.36
Mn	0.07
P	0.029
S	0.002
Ni	10.53
Cr	16.57
Mo	2.1
Cu	0.1
N	-

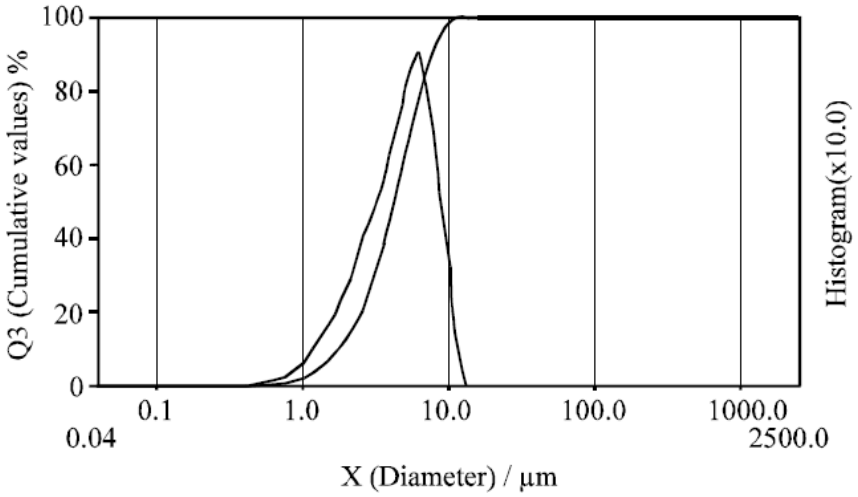

Figure 15: Particle size distribution of 316L SS -10PF [11]

4.2 FEEDSTOCK PREPARATION

The mass required for each component is determine below.

Density of each material are given as follow;

ρ_{SS} = 7.93 g/cm^{3,} ρ_{PW} = 0.93 g/cm^3, ρ_{PP} = 0.95 g/cm^3 , ρ_{SA}= 0.83 g/cm^3

For 67vol%,

Assuming total volume = 100cm^3;

Volume of stainless steel powder, V_{SS} = 67 cm^3

Volume of total binder, V_{TB} = 33cm^3

Volume of paraffin wax, V_{PW} = 70% X 33 cm^3 = 23.1 cm^3

Volume of polypropylene, V_{PP} = 25% X 33 cm^3 = 8.35 cm^3

Volume of stearic acid, V_{SA} = 5% X 33 cm^3 = 1.65 cm^3

Mass of stainless steel powder, m_{SS} =67 cm^3 X 7.93 g/cm^3 = 531.31 g

Mass of paraffin wax, m_{PW} = 23.1 cm^3 X 0.93 g/cm^3 = 21.483 g

Mass of polypropylene, m_{PP} = 8.35 cm^3 X 0.95g/cm^3 = 7.9325 g

Mass of stearic acid, m_{SA} = 1.65 cm^3 X 0.83 g/cm^3 = 1.3695 g

For 69vol%,

Assuming total volume = 100cm^3;

Volume of stainless steel powder, V_{SS} = 69 cm^3

Volume of total binder, V_{TB} = 31cm^3

Volume of paraffin wax, V_{PW} = 70% X 31 cm^3 = 21.7 cm^3

Volume of polypropylene, V_{PP} = 25% X 31 cm^3 = 7.75 cm^3

Volume of stearic acid, V_{SA} = 5% X 31 cm^3 = 1.55 cm^3

Mass of stainless steel powder, m_{SS} =69 cm^3 X 7.93 g/cm^3 = 547.17 g

Mass of paraffin wax, m_{PW} = 21.7 cm^3 X 0.93 g/cm^3 = 20.181 g

Mass of polypropylene, m_{PP} = 7.75 cm^3 X 0.95g/cm^3 = 7.3625 g

Mass of stearic acid, m_{SA} = 1.55 cm^3 X 0.83 g/cm^3 = 1.2865 g

All materials have been carefully weighted. The stainless steel powder was mixed with the binder using Z-blade mixer at temperature 180^{o}C for 90 min at speed of 60 rpm. After that, the feedstock was converted into granules.

4.3 TGA ANALYSIS ON FEEDSTOCK

TGA analysis of the binder and feedstocks was done. The results are shown in Appendix A. The comparison of the binder and feedstocks result is shown in Figure 16. Based on the figures, it can be conclude that the decomposition of the binder started about 200^{O}C. No residue was left at the end of the process for binder system. However, large residue were observed for both of the feedstocks. For 67vol% formulation, residue left are about 94wt% which are the same amount of steel powder wt% in the feedstock originally. For 69%, the residue left are 95wt%, which is steel powder in the feedstock.

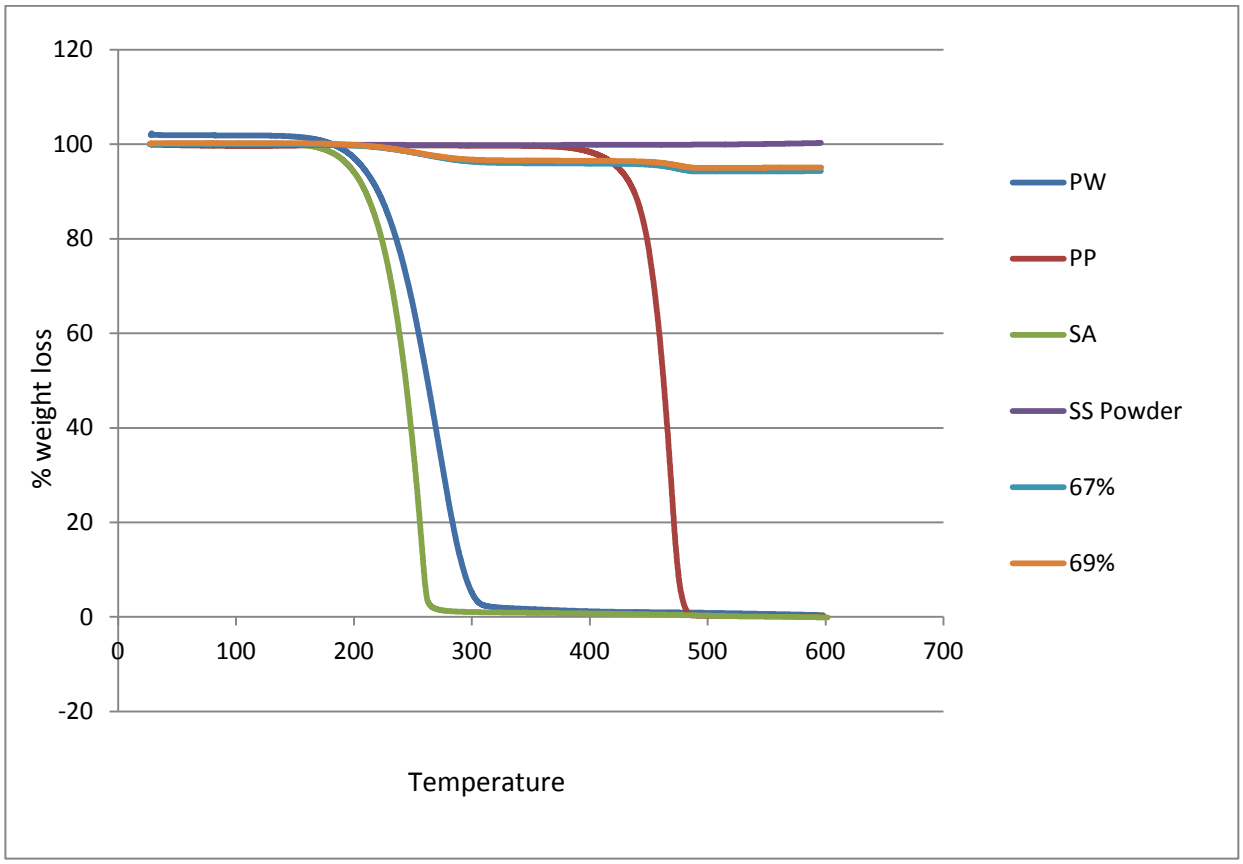

Figure 16: Comparison of TGA results on binder and feedstocks

4.4 RHEOLOGY

Rheology is the study of flowing matters. Viscosity and shear rate of the feedstock has been measured using CFT-500D/100D Shimadzu Flowtester Capillary Rheometers. Viscosity is a measure of the resistance to flow[16]. The capillary rheometer measures the feedstock viscosity using the flow resistance of the melted feedstock to flow through the die orifice. The feedstock is charged in the heated cylinder to melt. After a specified time, the feedstock melt is extruded with constant force by the piston, through the die orifice[15].

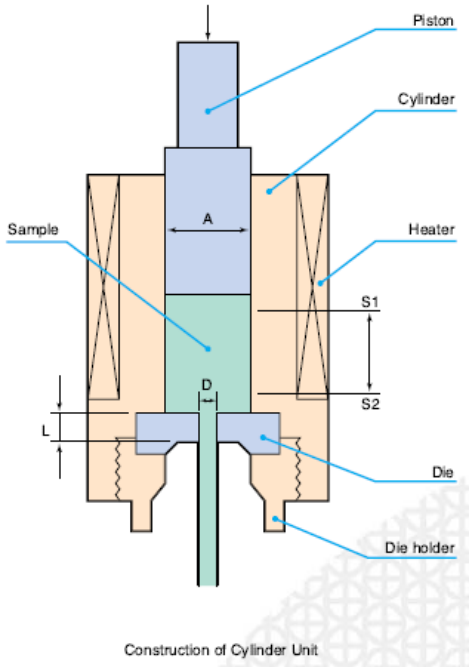

Figure 17: Construction of Cylinder Unit in Capillary Rheometer[15]

The viscosity is calculated using formula below[15]:

i. Flow Rate, Q

$$Q = A \cdot \frac{S2-S1}{10.\Delta t}$$

A - piston cross sectional area (cm^2)

S1 - Calculation start point (mm)

S2 - Calculation end point (mm)

Δt - Piston travel time from S1 to S2 (sec)

ii. Apparent shear rate, γ

$$\gamma = \frac{32\ Q}{\pi\ (D^3)} \cdot 10^3$$

D - die orifice diameter (mm)

iii. Apparent shear stress, τ

$$\tau = \frac{PD}{4L}$$

P - Test pressure (Pa)

D - die orifice diameter (mm)

L - Die length (mm)

iv. Apparent viscosity, η

$$\eta = \frac{\tau}{\gamma}$$

The rheological behaviors of both feestock were studied at different temperature ranging from 140 to 170^{o}C. The result is shown below.

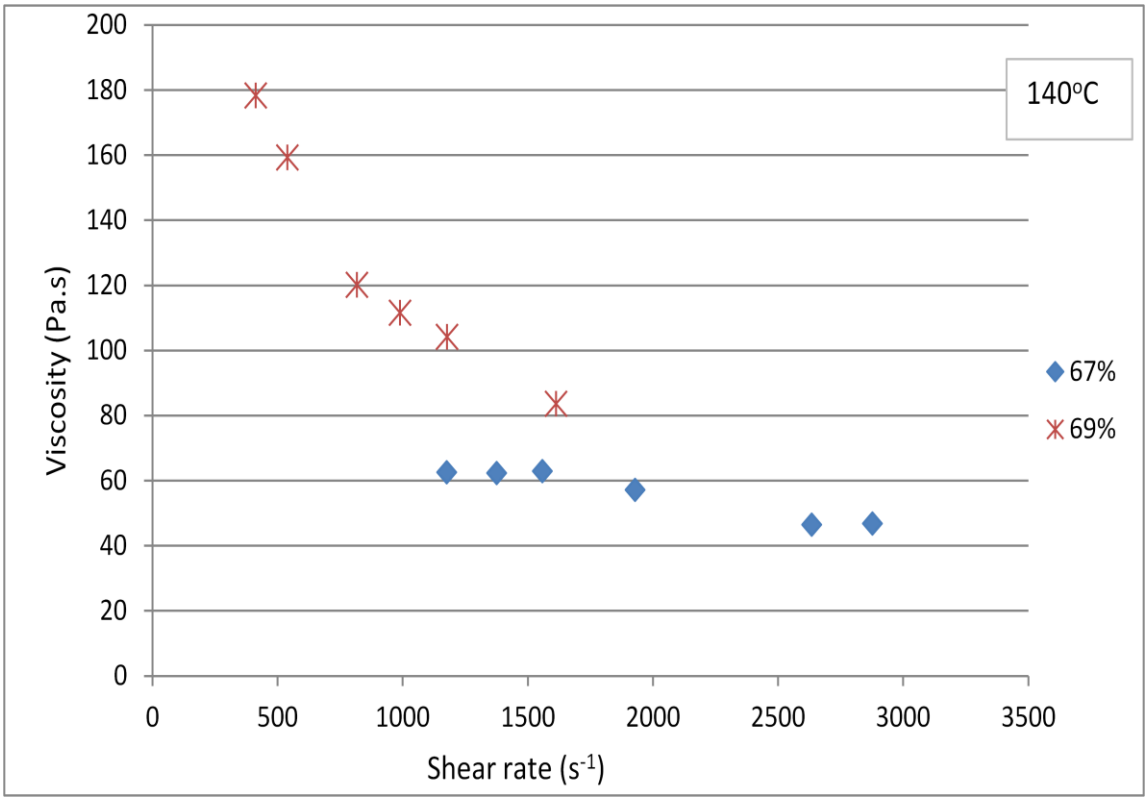

Figure 18: Viscosity vs Shear Rate for both feedstocks at 140^{O}C

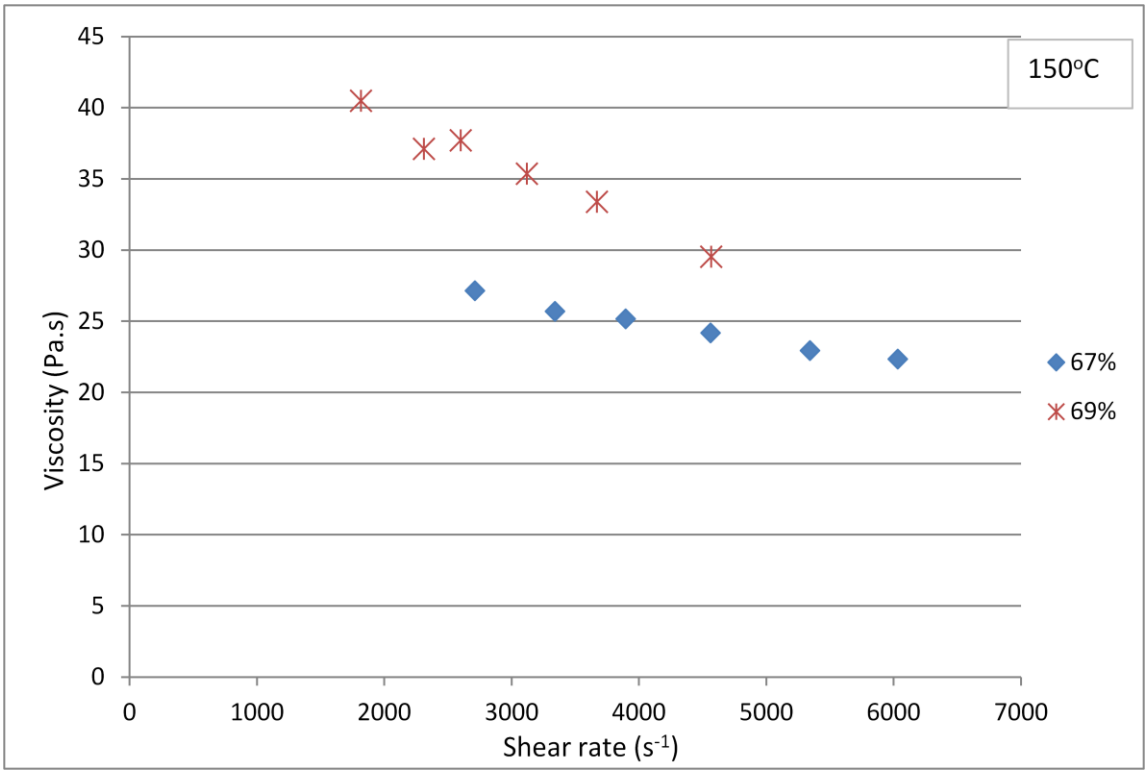

Figure 19: Viscosity vs Shear Rate for both feedstocks at 150^{O}C

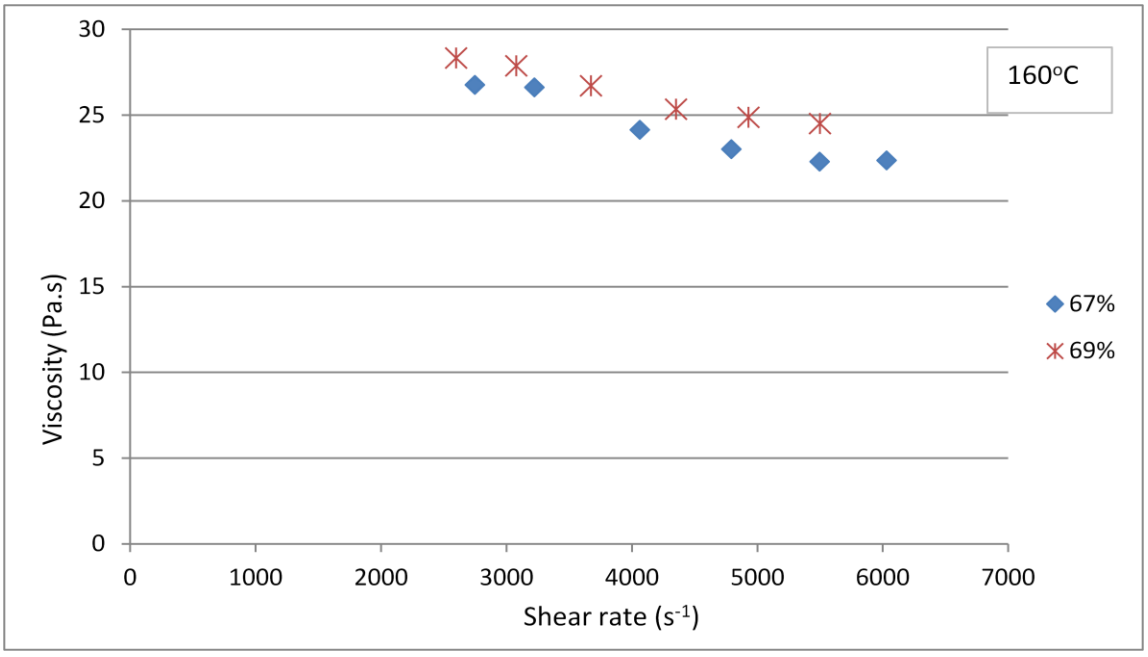

Figure 20: Viscosity vs Shear Rate for both feedstocks at 160^{O}C

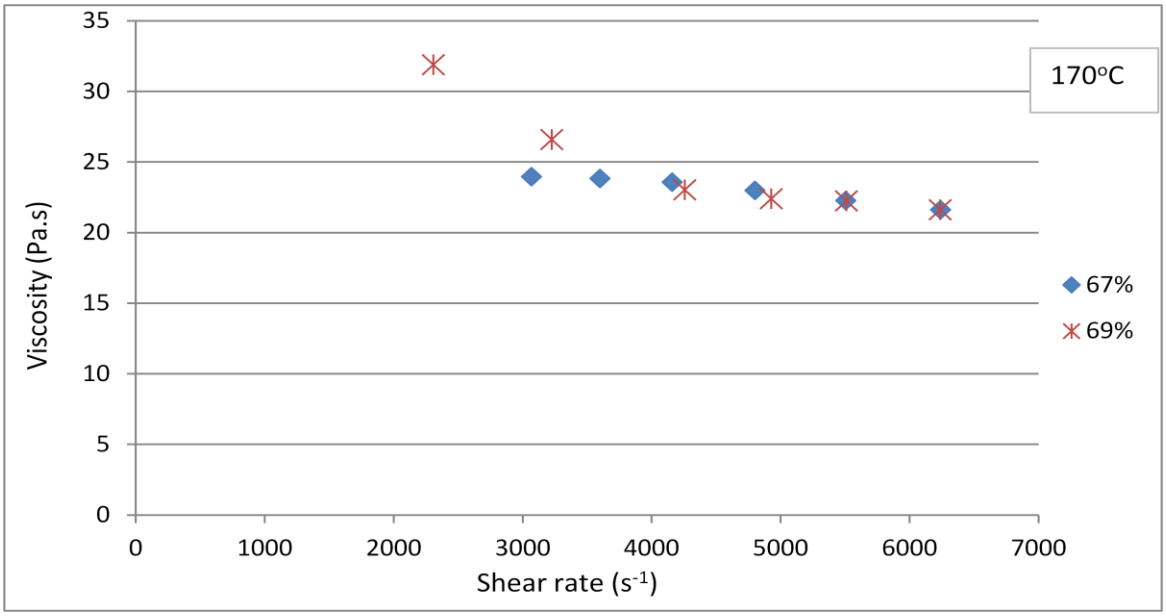

Figure 21: Viscosity vs Shear Rate for both feedstocks at 170^{O}C

From the graphs, it is clear that both of the feedstock showed Pseudoplastic behavior also known as shear thinning behavior. The viscosity of the feedstocks decreased with increasing of shear rate. The viscosity should be less than 1000 Pa.s in shear rate range of 10^2 to 10^5 s^{-1} is necessary for PIM [8]. It can be concluded that both of the feedstocks are suitable for PIM.

4.5 PHYSICAL EXAMINATION

Physical examination is carried out for each molded sample. No defects were observed on the samples. The mass of each samples are recorded as well as their dimension. The data recorded shown in Table 6 and 7.

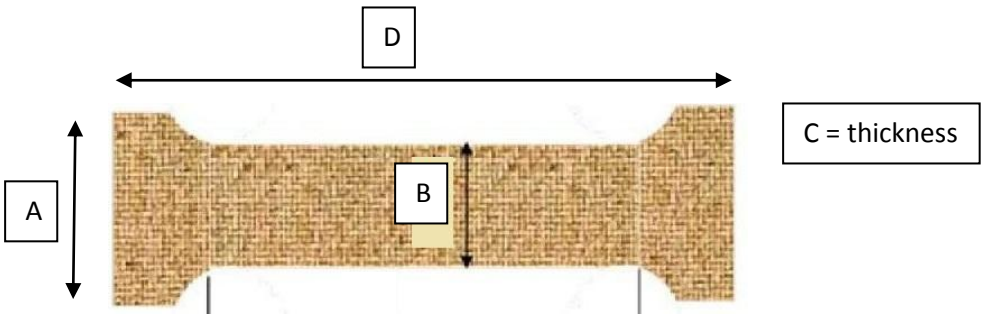

Figure 22: Dimension of Injection Molded Parts

Table 6: Measurement of 67vol% molded samples

Sample	Measurement (mm)				Mass (g)
	A	B	C	D	
	Average	Average	Average	Average	
2	14.957	5.997	3.137	85.660	14.793
3	14.953	6.000	3.107	85.703	14.865
4	14.923	6.047	3.100	85.670	14.674
6	14.890	5.980	3.050	85.443	14.170
7	14.920	5.977	3.077	85.567	14.447
8	14.890	5.987	3.060	85.470	14.181
9	14.887	6.030	3.057	85.410	14.077
11	14.993	6.023	3.067	85.847	15.102
12	14.927	5.977	3.050	85.527	14.302
13	14.923	5.980	3.040	85.523	14.074
14	14.973	5.977	3.057	85.603	14.492
15	14.900	5.990	3.047	85.557	14.267
16	14.960	6.003	3.060	85.563	14.378
17	14.940	6.003	3.110	85.623	14.561
18	14.953	5.980	3.060	85.497	14.076
19	14.930	6.000	3.060	85.593	14.376
21	14.937	5.960	3.063	85.553	14.523
22	14.960	5.983	3.063	85.787	15.068
23	14.923	5.977	3.057	85.717	14.646
24	14.893	5.967	3.033	85.567	14.453
25	14.877	5.967	3.033	85.413	14.025
26	14.850	5.963	3.027	85.460	14.011
27	14.933	5.987	3.037	85.580	14.349
28	14.923	5.997	3.043	85.670	14.592
29	14.867	5.977	3.027	85.270	13.571
30	14.953	6.003	3.060	85.773	15.082
31	14.853	5.967	3.077	85.330	13.809
32	14.933	5.987	3.050	85.703	14.809
33	14.953	5.997	3.050	85.723	14.984
34	14.890	5.963	3.067	85.397	13.984

Table 7: Measurement of 69vol% molded samples

Sample	Measurement (mm)				Mass (g)
	A	B	C	D	
	Average	Average	Average	Average	
1	14.943	5.980	3.077	85.660	14.757
2	14.960	6.047	3.053	85.750	15.027
3	14.967	5.987	3.077	85.743	15.023
4	14.950	5.987	3.063	85.677	14.868
5	14.950	5.970	3.067	85.883	15.292
6	14.910	5.987	3.057	85.677	14.805
7	14.940	5.970	3.067	85.763	14.842
8	14.960	5.980	3.053	85.847	15.198
9	14.937	5.983	3.053	85.847	15.101
10	14.923	5.957	3.060	85.653	14.784
11	14.943	5.973	3.053	85.813	15.143
12	14.947	5.970	3.070	85.663	14.887
13	14.913	5.977	3.060	85.687	14.859
14	14.953	5.997	3.057	85.860	15.364
15	14.960	5.970	3.070	85.830	15.368
16	14.937	6.010	3.060	85.797	15.179
17	14.960	5.993	3.063	85.813	15.249
18	14.957	6.000	3.063	85.787	15.164
19	14.923	5.973	3.057	85.637	14.864
20	14.957	5.997	3.057	85.850	15.281
21	14.977	6.000	3.060	85.820	15.337
22	14.967	5.983	3.107	85.837	15.274
23	14.933	6.057	3.050	85.660	14.840
24	14.957	5.977	3.077	85.833	15.337
25	14.950	5.993	3.053	85.650	14.800
26	14.940	5.977	3.063	85.760	15.050

4.6 DEBINDING

4.6.1 Solvent Extraction

The major binder, Paraffin Wax, is soluble in organic solvent. Therefore, the solvent debinding process is carried out. The solvent debinding is done at 60^{o}C. This is because [10] investigate that the higher the temperature, the higher the amount of binder extracted(wt.%). However, if the temperature too high, it can caused defects such as cracks to the sample. The samples are immersed in n-heptane up to 7 hours. The debinder removal ratio is determine using following equation :

$$Wd(\%) = (Wi - W) / Wi \times 100$$

where Wi – initial weight of compressed bodies, W – weight after solvent debinding. Then, the amount of binder extracted is calculate by dividing Wd by the total binder content (wt%) in the feedstock. The result is shown in the table and figure below.

Table 8: Solvent debinding results

Sample	Minutes	F1					F2				
		W_i [Before]	W [After]	W_d	W_d (%)	% of Extracted Wax	W_i [Before]	W [After]	W_d	W_d (%)	% of Extracted Wax
1	10	7.373	7.308	0.0088	0.8816	23.20	7.489	7.358	0.0175	1.7492	49.98
2	30	7.068	6.986	0.0116	1.1602	30.53	7.728	7.526	0.0261	2.6139	74.68
3	60	7.281	7.158	0.0169	1.6893	44.46	7.549	7.321	0.0302	3.0203	86.29
4	90	7.066	6.945	0.0171	1.7124	45.06	8.412	8.145	0.0317	3.1740	90.69
5	120	7.246	7.088	0.0218	2.1805	57.38	7.598	7.327	0.0357	3.5667	101.91
6	180	7.301	7.171	0.0178	1.7806	46.86	7.630	7.366	0.0346	3.4600	98.86
7	240	7.363	7.168	0.0265	2.6484	69.69	7.007	6.781	0.0323	3.2253	92.15
8	300	7.690	7.416	0.0356	3.5631	93.76	7.735	7.457	0.0359	3.5941	102.69
9	360	7.696	7.393	0.0394	3.9371	103.61	7.770	7.469	0.0387	3.8739	110.68
10	420	6.376	6.133	0.0381	3.8112	100.29	7.416	7.164	0.0340	3.3981	97.09

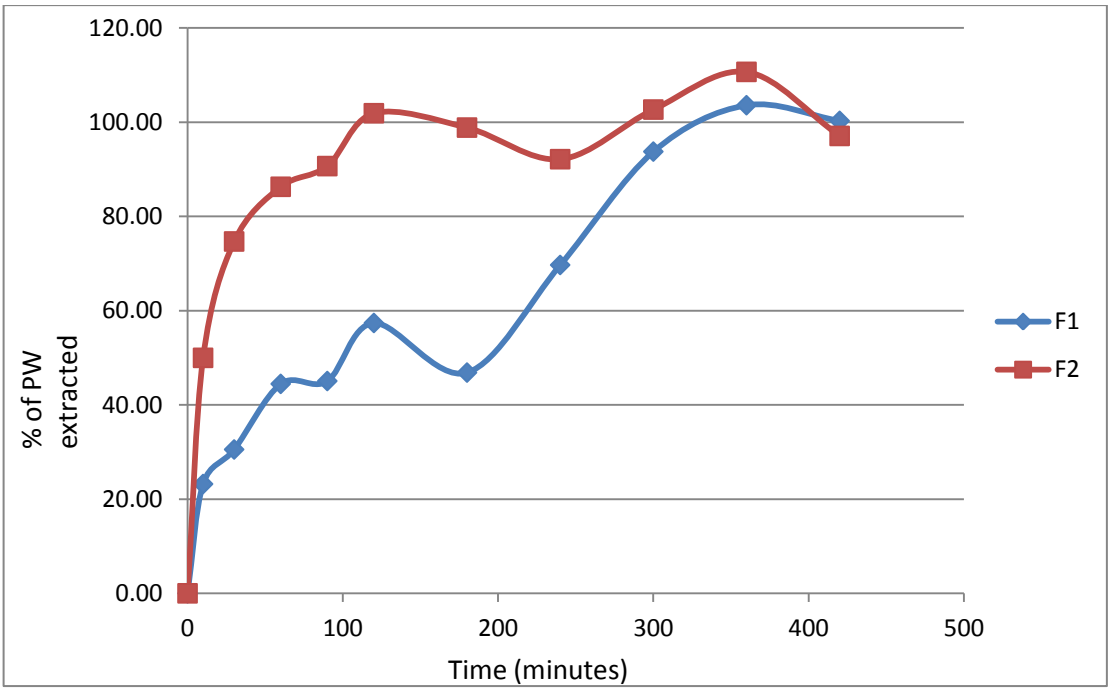

Figure 23: Percentages of PW extracted versus time

As we can see in the graph, it takes about 5 hours to remove the Paraffin Wax completely from the green parts. No physical defects are observed in both green samples.

4.6.2 Thermal Debinding

The test samples then were thermally debond to remove the rest of the binders (Polypropylene and Stearic Acid). The process is done with different heating rates (3^{o}C/min, 5^{o}C/min, 7^{o}C/min and 10^{o}C/min) to dwell temperature of 450^{o}C. The dwell time is 1 hour.

The test samples were successfully debond for all heating rates. However, for 10^{o}C/min, the samples are observed with cracks on the surface and swelling on both formulation test samples. Based on the results, it was concluded that the most suitable heating rate for thermal debinding is 7^{o}C/min. The micrographs of the debonded samples are shown in figures below.

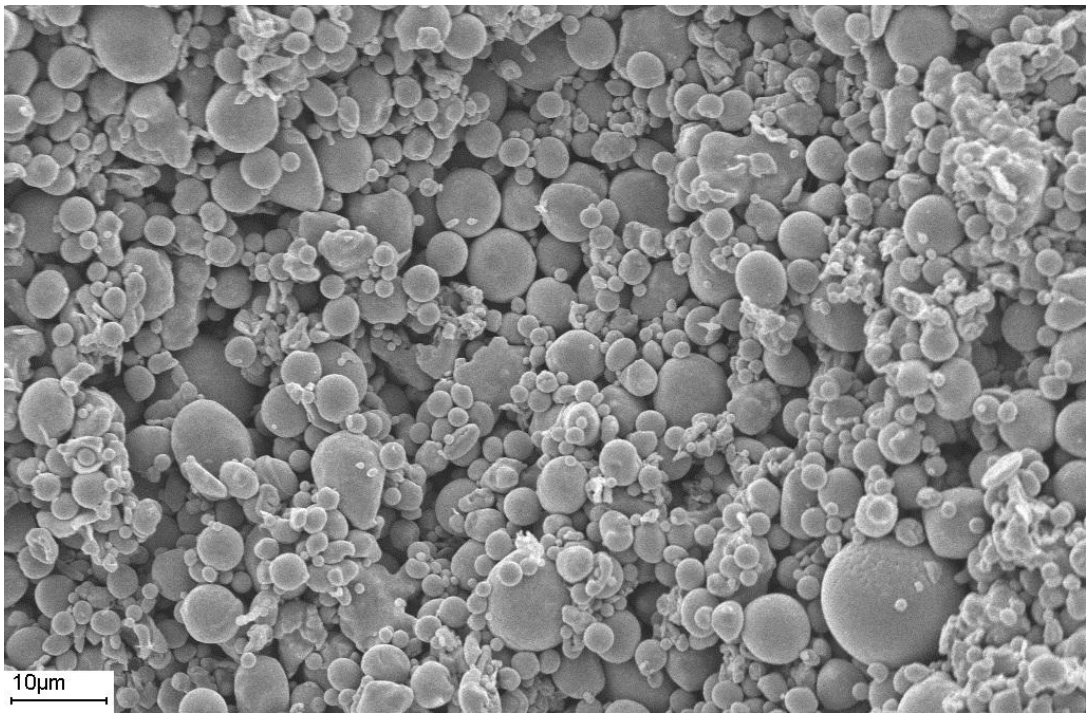

Figure 24: SEM micrograph of debonded F1 (67%) at 1000X

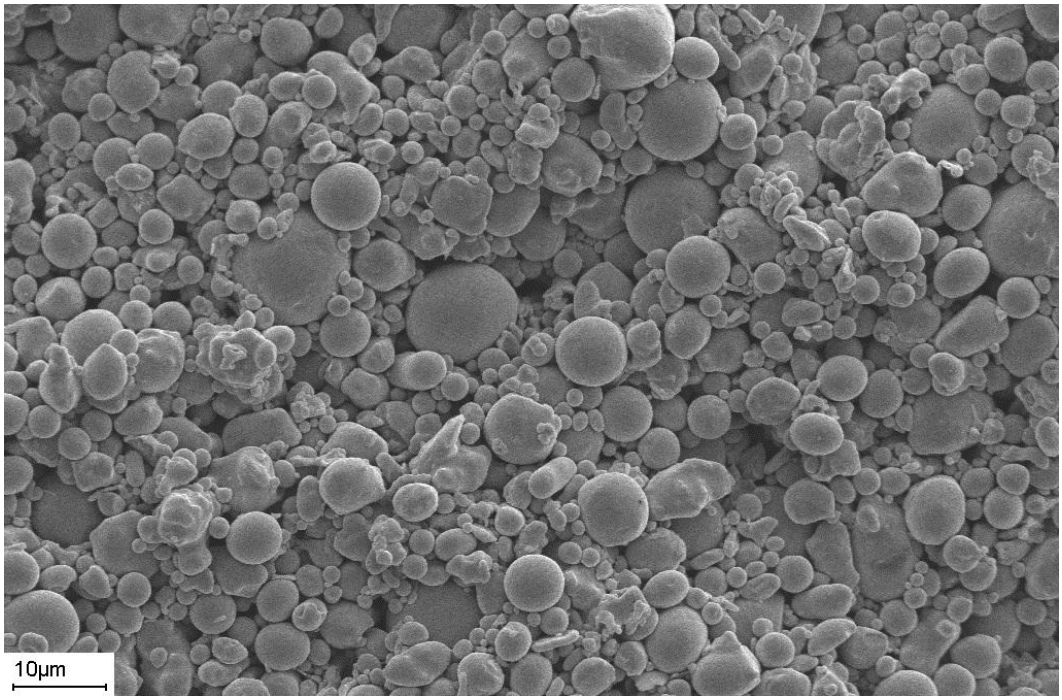

Figure 25: SEM micrograph of debonded F2 (69%) at 1000X

CHAPTER 5
CONCLUSION

This study concluded that

- The viscosity of both formulations is within range required for PIM.
- For both solid loading, 67%vol and 69%vol, the rheological behaviour showed pseudoplastic behaviour.
- The solvent extraction temperature and time to extract major binder from green parts without causing any defects to green parts is identified at 60^{o}C and 5 hours.
- For thermal debinding temperature, heating rate and time is 450^{o}C, 7^{o}C/min and 1 hour for both formulations, respectively.

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APPENDICES

APPENDIX A

TGA ANALYSIS RESULT

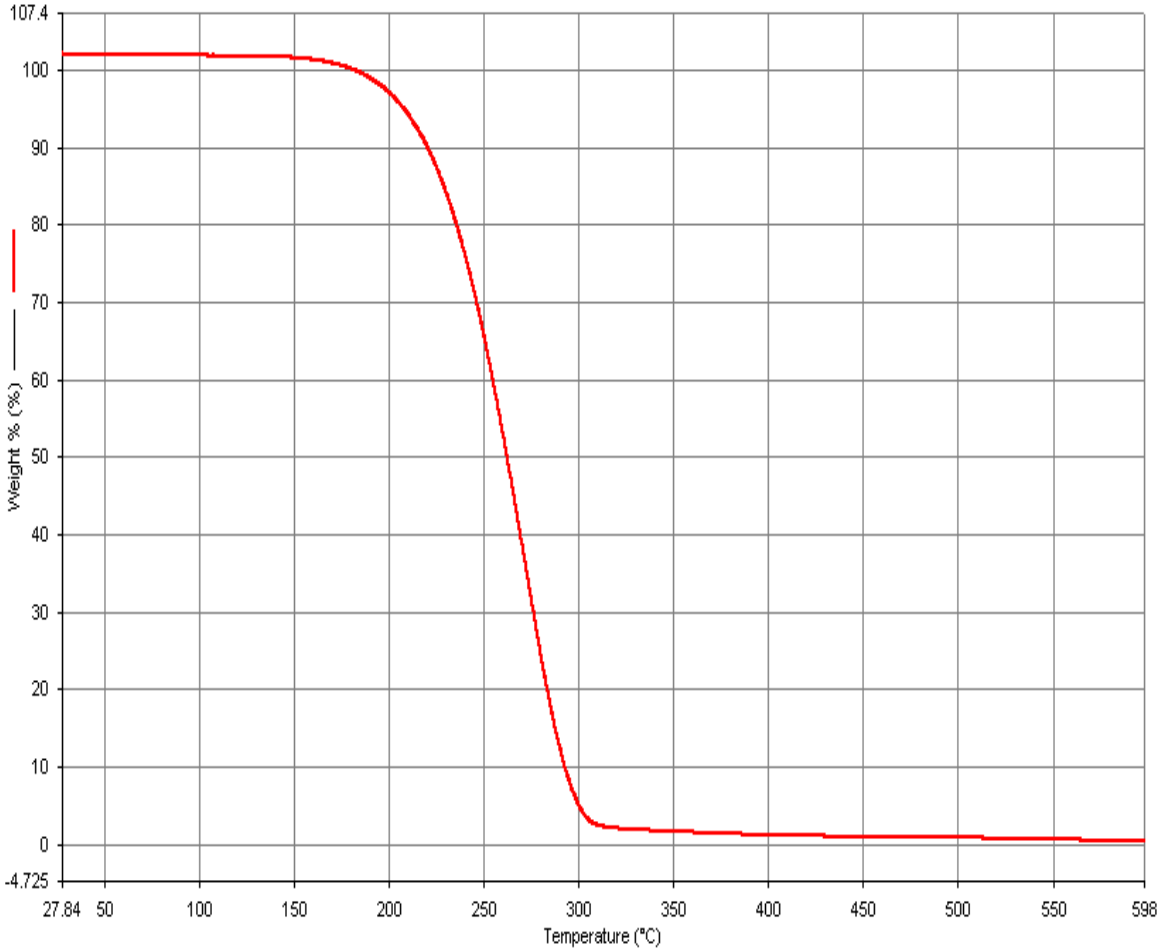

Figure 26: Result for TGA analysis of PW

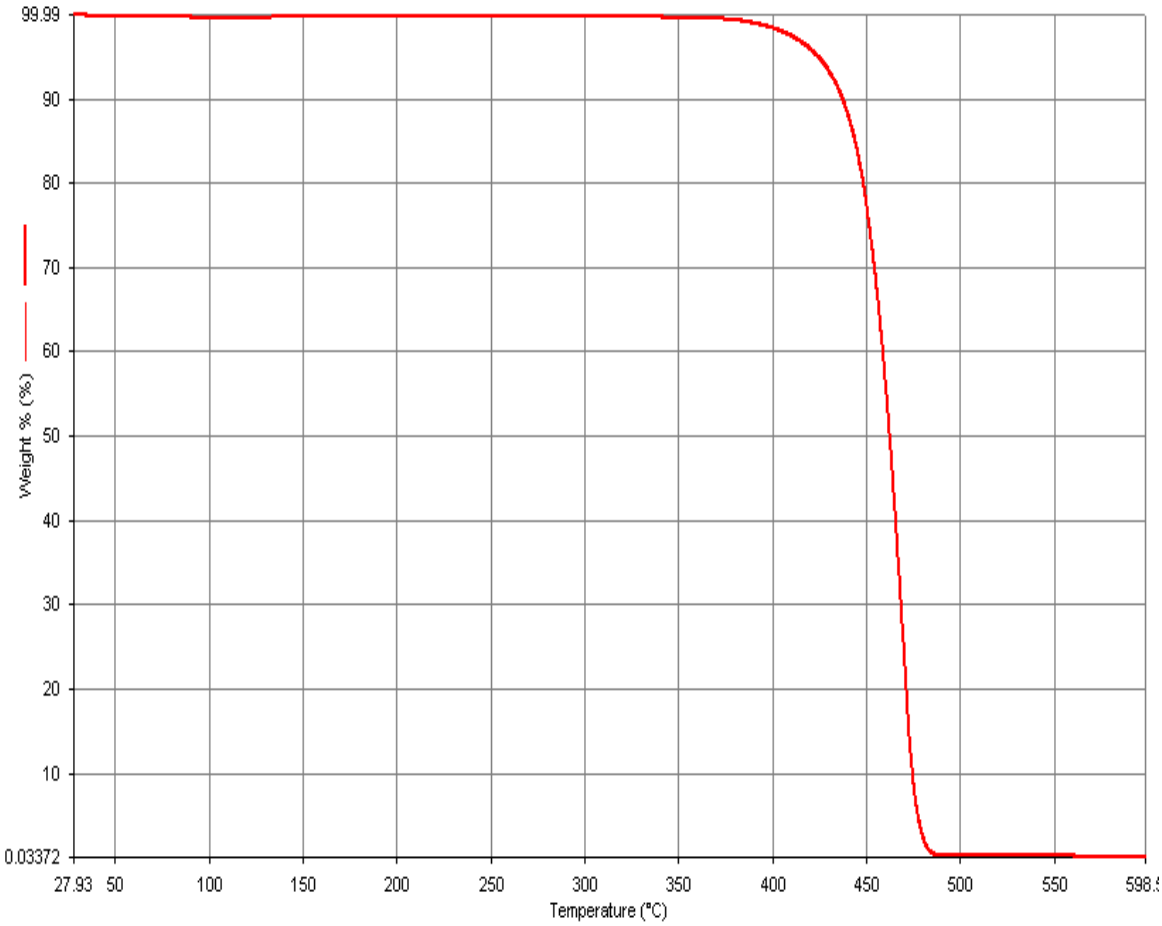

Figure 27: Result for TGA analysis of PP

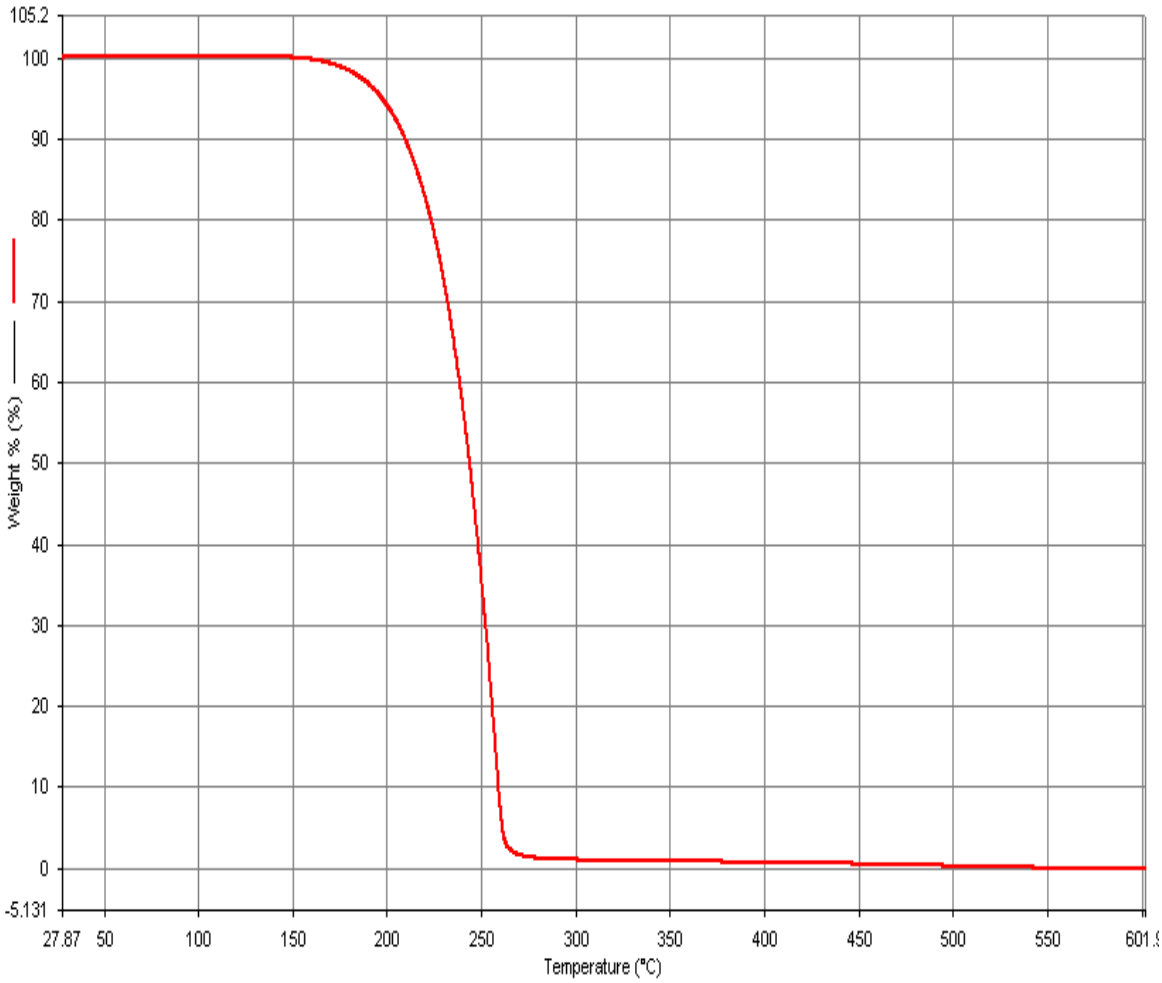

Figure 28: Result for TGA analysis of SA

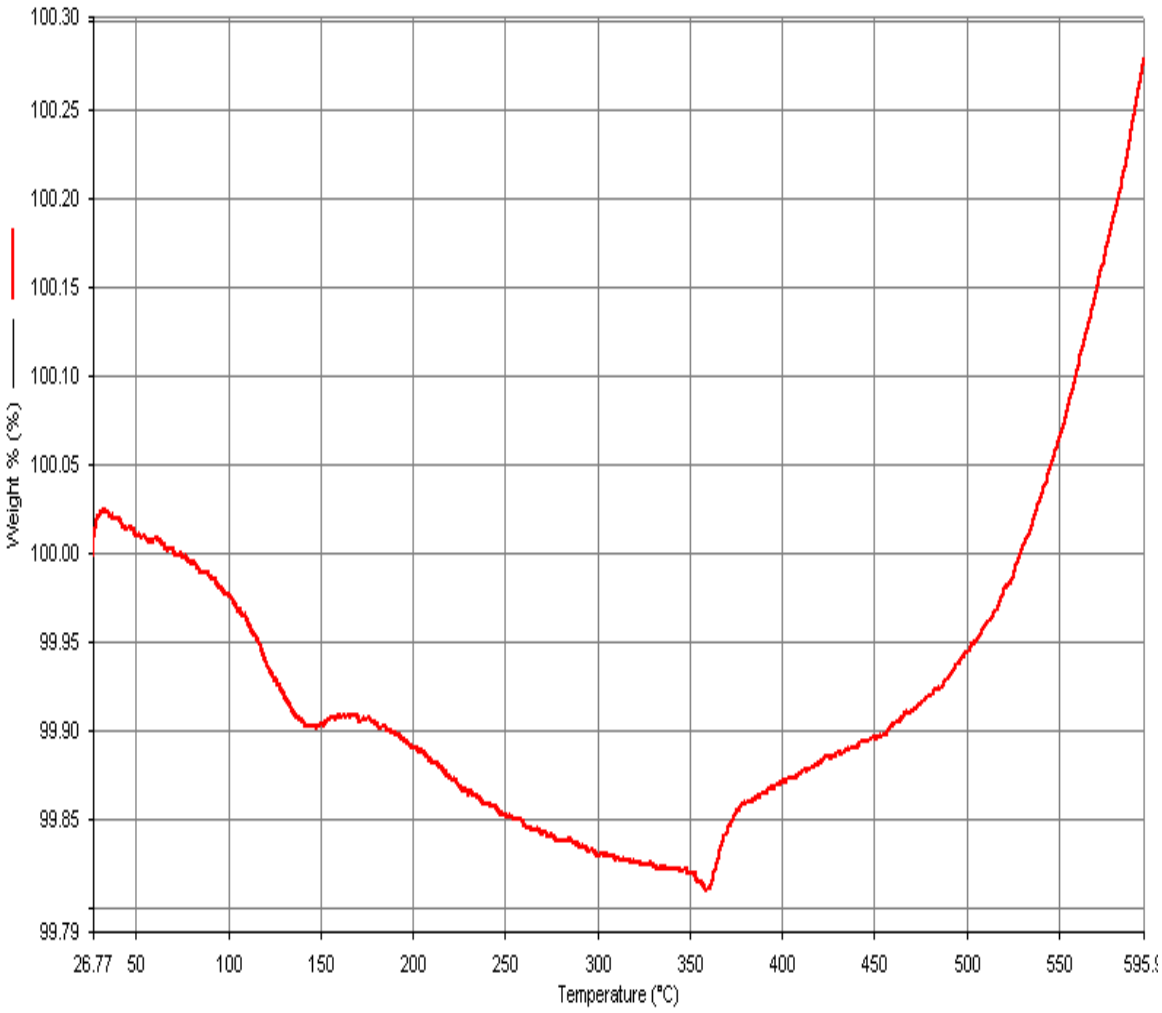

Figure 29: Result for TGA analysis of SS Powder

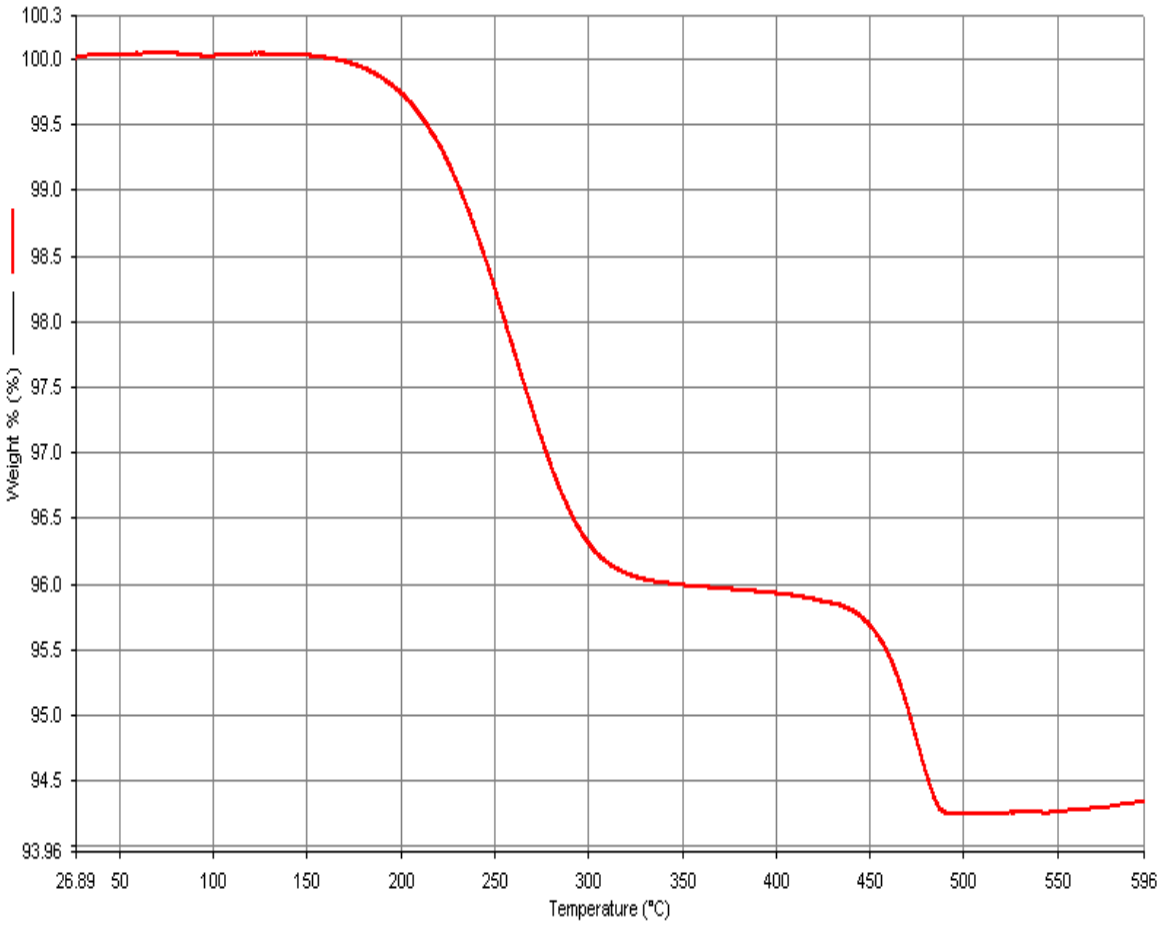

Figure 30: Result for TGA analysis of 67% Feedstock

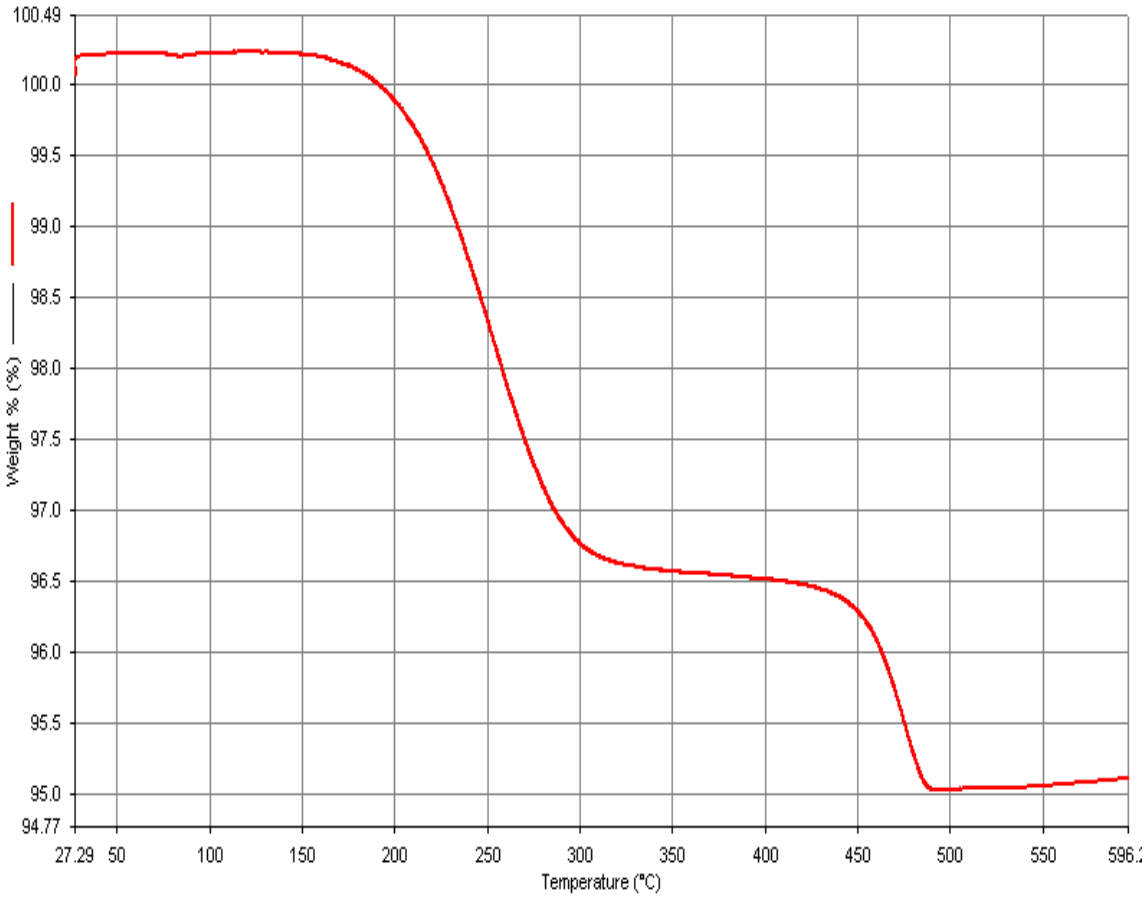

Figure 31: Result for TGA analysis of 69% Feedstock