

## Thermal Debinding Study of Waste Polystyrene as A Sustainable Binder in Metal Injection Molding

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**Abstract:** Metal injection molding (MIM) is one of most sought commercial process in making intricate metal parts in bulks quantity. Many researchers commonly used commercial binders in MIM and only a few of them were using recycle materials as a binder. In this study, the usage of waste polystyrene as one of the binder material will be observed. The binder system used is a combination of palm kernel (PK) and waste polystyrene (WP) to produce a “green MIM” technology. The feedstock used to produce green part was made with a mixture of Stainless Steel 316L (SS316L) metal powder with the size of 6 $\mu$ m and a binder system which consist of 60 % waste polystyrene and 40 % palm kernel. Thermal Gravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) were done to identify the degradation and melting temperature of binders. However, this study focuses more on thermal debinding of waste polystyrene in MIM technology. After the process of injection molding and solvent debinding, thermal debinding will be carried out. During this process, three samples were analysed. The thermal debinding of these three sample were conducted by using three different debinding temperature at 500 °C, 550 °C and 600 °C. The heating rate, dwell time and cooling rate were kept at constant values of 2 °C/min, 60 minutes and 5 °C/min respectively throughout the whole debinding process. It was recorded that only sample 3 which was thermally debinded at 600°C had the brown density of 80.30% which exceeding the theoretical value of 80%. This study revealed that waste polystyrene can be optimally used as a binder material in MIM technology and was able to thermally degraded successfully without problem.

**Keywords:** MIM, Thermal, Debinding, Waste Polystyrene, Stainless Steel 316L

## 1. Introduction

Metal injection molding (MIM) is one of a manufacturing method to produce metal parts. It has been recognized as a method to produce complex and intricate metal parts in a bulk quantity production. The primary idea of MIM was to combine the shaping benefit of injection molding and higher strength and stiffness of the molded metal parts[1]. In MIM technology the feedstock is made up by a binder and metal powders. Fine metal powders are mixed with suitable binder.

Binder in a feedstock is a main reason that provided metal powders' flow smoother and easy to inject. The role of the binder is purely to provide the feedstock mix with mold ability and shape retaining properties. Binder usually consist of two types which is primary binder and secondary binder. Primary binder often made of wax or oil materials while secondary binder commonly made of polymers like polystyrene[1]. After that, both of the binders will be removed by a method called debinding. Debinding has a wide variety of option and one of them is thermal debinding. Thermal debinding is a method using thermal to remove the binders. Before sintering, the metal components were slowly heated according to the temperature to decompose binders.

### 1.1 Aim

The aim of this study is to produce a good quality feedstock from the combination of waste polystyrene (WP) and Palm Kernel (PK) as binder system while stainless steel (SS316l) as its metal powder.

### 1.2 Objectives

There are two objectives of this research. The first one is to study the waste polystyrene diffusion during thermal debinding process and the other one is to evaluate the physical properties of brown part (part called after thermal debinding, before sintering) by examining the density and microscopic structure of the part.

## 2. Materials and Methods

Metal injection molding process include feedstock preparation, binder system, debinding and sintering [2].

### 2.1 Feedstock

The feedstock materials used are SS316L as metal powder, waste polystyrene (WP) as a primary binder and palm kernel oil (PKO) that acts as secondary binder[3]. Water atomized SS316l that having irregular shape with mean size  $d_{50}$  6  $\mu\text{m}$  supplied by Epson Atmix Japan was selected in this process as a metal powder. SS316L was chosen because it was easy to find, high corrosion resistance, excellent biocompatibility, affordable and good fabrication. For the binder system, the composition consists of 60 % of waste polystyrene and 40 % of palm kernel. The feedstock will be grinded and mixed using grinding machine and rotary mixer before being injected through horizontal MIM machine.

### 2.2 Binders

The binder's characteristics such as its thermal degradation and melting temperature for both waste polystyrene and palm kernel were determined by using Thermal Gravimetric Analysis (TGA) and Differential Thermal Analysis (DTA).

### 2.3 Thermal debinding

Thermal debinding process was done in order to remove polymer based binder[4]. Thermal debinding often done after solvent debinding and before sintering. The mechanism used in this process was thermal degradation[5]. Thermal debinding process was done using a Tube Furnace.

### 3. Results and Discussion

#### 3.1 Binder determination

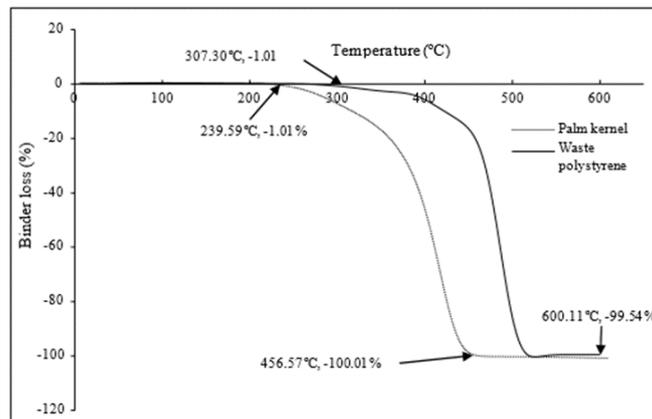
The density of waste polystyrene and palm kernel were determined using Density Analytical Balance via Archimedes principles. For the accuracy of result taken, temperature of distilled water was an important factor. Table 3.1 below shows the density on binders. The density of binders was important as it was used to calculate feedstock composition. The density values of waste polystyrene and palm kernel were 0.906 g/cm<sup>3</sup> and 0.9087 g/cm<sup>3</sup> respectively.

**Table 3.1: Density of binders**

Binders	Density (g/cm <sup>3</sup> )
Waste polystyrene	0.906
Palm kernel	0.9087

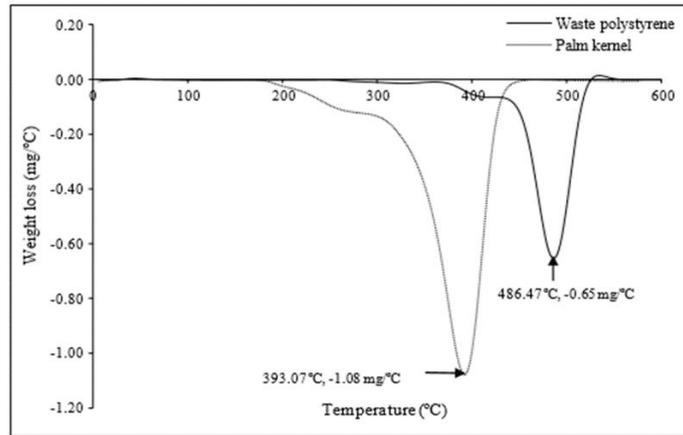
#### 3.2 Degradation temperature

Appropriate amount of waste polystyrene (WP) and palm kernel (PK) were placed inside the TGA decibels. The analysis of both specimens were conduct at temperature range from room temperature to 600°C with the heating rate of 10 °C/min. Figure 3.1 below shows the TGA curves for both waste polystyrene and palm kernel. WP starts to degrade at 307.29 °C which the weight loss of WP is 1.01 % and finish at 600.11 °C with the weight loss of WP is 99.54 %. Whereas for the second binder, PK, started to degrade at the range temperature of 239.59 °C to 456.57 with the weight loss of PK is 1.01% and -100.01% respectively.



**Figure 3.1: TGA curves for both waste polystyrene and palm kernel**

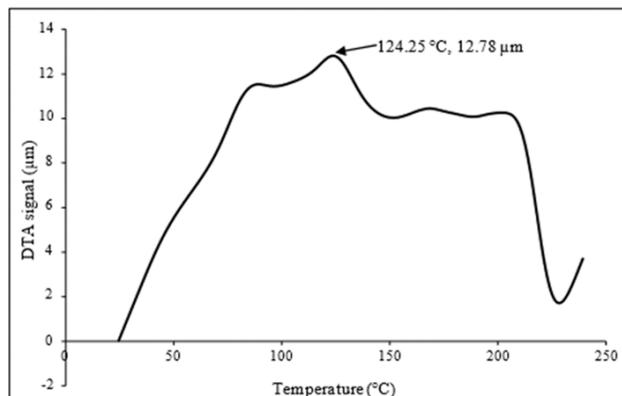
Another curves that can be extracted from TGA was the optimum curves of binder degradation as shown in the figure 3.2 below. The figure shows that the optimum degradation temperature for waste polystyrene was at 486.47°C where the weight loss of waste polystyrene was 0.65mg during this particular temperature. The other curve shows that palm kernel best degraded at 393.07°C where the weight loss of palm kernel was 1.08mg at the temperature. Overall, both binders can be considered of having wide range of degradation temperature which is useful for faster debinding process, less defects and ease the shape retention[6]. Other than that, TGA curves were used to design thermal debinding circle[7]. The binders were removed at above the maximum degradation values.



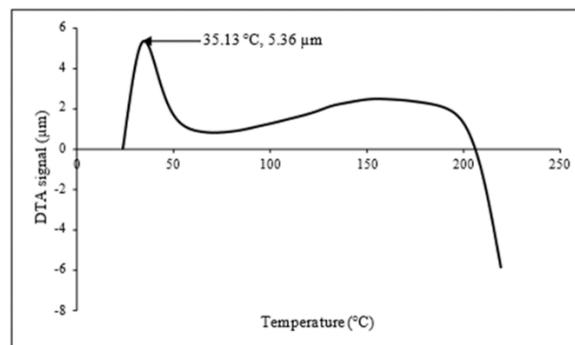
**Figure 3.2: The optimum curves of binder degradation**

### 3.3 Melting temperature

The binder's melting temperature was determined using Differential Thermal Analysis (DTA). The optimal melting point of binder located at the peak of DTA curve. Figure 3.3 shows that the optimal melting point for waste polystyrene was 124.25 °C while figure 3.4 shows that palm kernel's melting temperature was at temperature of 35.12 °C.



**Figure 3.3: The melting graph of waste polystyrene**



**Figure 3.4: The melting graph of palm kernel**

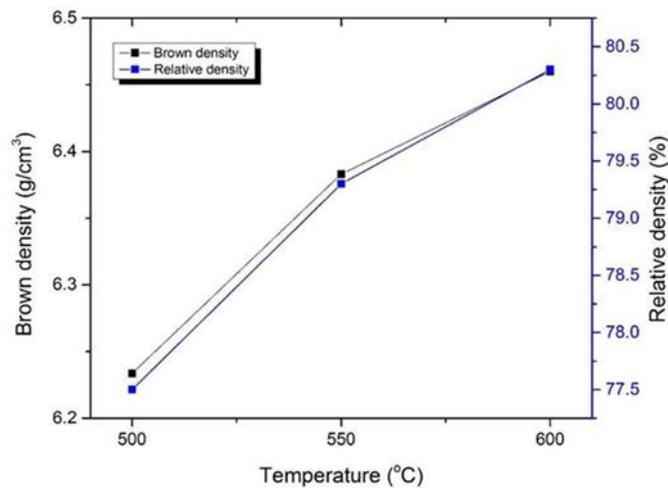
### 3.4 Thermal debinding determination

The backbone binder which is waste polystyrene will be removed completely via thermal debinding[8]. Prior to thermal pyrolysis, the network of waste polystyrene binding and holding the metal powder particle together. Then, thermal debinding was proceed to eliminate all of binder in the green part without causing defects[9]. Table 3.2 below shows the experiment of thermal debinding values.

**Table 3.2: Experiment of thermal debinding**

Sample	Temperature (°C)	Heating		Cooling
		rate (°C/min)	Dwell time	rate
			(min)	(°C/min)
1	500			
2	550	2	60	5
3	600			

The thermal debinding process was done by keeping heating rate at 2°C/min, 60 minutes of dwell time and 5°C/min cooling rate at constant through the study. Since three different heating temperature were used, the influence of debinding temperature on brown density was studied. What is important for this study was to make sure that the brown part was having an adequate strength before proceeding for the next process because brown part apparently need more appropriate handling due to its brittle structure[10]. Figure 3.5 below shows both brown and relative density when thermal debinding is performed at temperature of 500 °C, 550 °C and 600 °C. From the figure, we can see that both brown and relative density increased as the debinding temperature increase. It also shows that at debinding temperature of 600°C, both densities were at its highest peak.



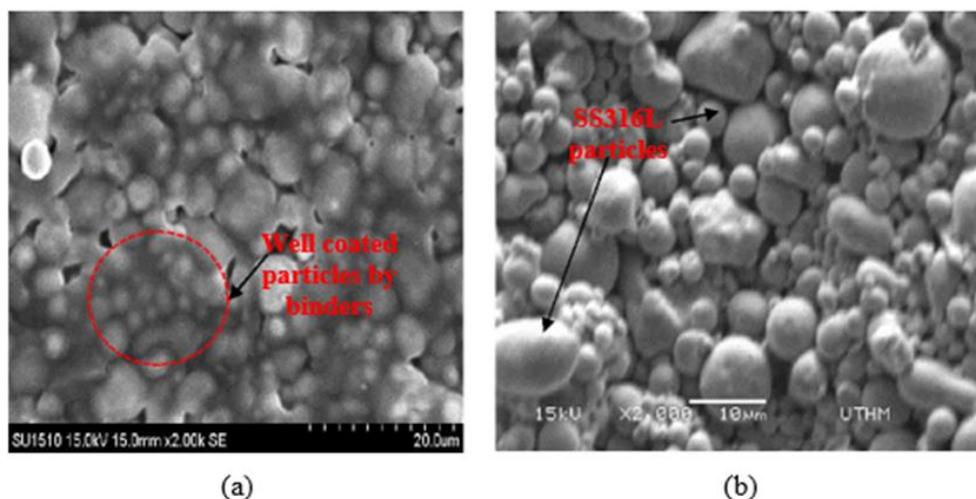
**Figure 3.5: Brown density and relative density of brown part at various temperature between 500°C and 600°C**

According to one of the previous research, the brown density should exceed 80% of their theoretical values[11]. Referring at the figure above, only sample 3 was exceeding this theoretical values at 80.30%. Sample 3 was thermally debinded at temperature of 600°C. As for sample 1 and 2 which thermally debinded at temperature 500°C and 550°C respectively, achieved the relative density of 77.50 % and 79.50 %. Thus, it was summarized that the solvent part needed to thermally debinded at 600°C to achieve the best result. During the trials, all brown parts were free from defect. Figure 3.6 shows the free defects brown part.



**Figure 3.6: Free defect brown part**

Figure 3.7 below gives the details on morphology comparison of both green and brown parts when giving magnification of 2000x using SEM. For Figure 3.7 (a), it illustrates that the metal particles surface was covered with binders. The gap among the particles also filled with binders. As for Figure 3.7 (b), it shows the typical brown part after the removal of both waste polystyrene and palm kernel. The SEM image also shown the waste polystyrene and palm kernel strands that were successfully removed to specify the successful thermal debinding process.



**Figure 3.7: Morphology comparison of SEM image at 2000x for (a) green part and (b) brown part**

#### 4. Conclusion

The analysis done for the brown part after thermal debinding process shows that the brown part was free from any defects. The brown part produced using 600°C debinding temperature recorded a rather high density, valued by 80.3%. This test density value exceed the standard theoretical density desired for waste polystyrene elimination during thermal debinding. The morphology observation done to the brown part showed that all binders eliminated and porous structure was exhibited after it as thermally debinded at 600°C. Thus, it proved that the uses of waste polystyrene were recommend in MIM technology and it cause no harm to the parts during the process.

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#### References

- [1] S. Engström, “Metal Injection Molding : A Review Of The MIM Process and Its Optimization,” *Degree Thesis*, pp. 1–68, 2017, [Online]. Available: <https://pdfs.semanticscholar.org/0e99/65fe942dc90ee587824cda08b1b423fb1bd4.pdf>.
- [2] R. Asmawi, M. H. I. Ibrahim, and A. M. Amin, “Mixing and characterisation of stainless steel 316L feedstock for waste polystyrene binder system in metal injection molding (MIM),” *Appl. Mech. Mater.*, vol. 607, pp. 83–86, 2014, doi: 10.4028/www.scientific.net/AMM.607.83.
- [3] R. Asmawi, M. H. I. Ibrahim, A. M. Amin, and N. Mustafa, “Characterization of Stainless Steel 316L Feedstock for Metal Injection Molding (MIM) Using Waste Polystyrene and Palm Kernel Oil Binder System,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 160, no. 1, 2016, doi: 10.1088/1757-899X/160/1/012062.
- [4] K. S. Hwang, H. K. Lin, and S. C. Lee, “Thermal, solvent, and vacuum debinding mechanisms of PIM compacts,” *Mater. Manuf. Process.*, vol. 12, no. 4, pp. 593–608, 1997, doi: 10.1080/10426919708935169.
- [5] S. J. Park, Y. Wu, D. F. Heaney, X. Zou, G. Gai, and R. M. German, “Rheological and thermal debinding behaviors in titanium powder injection molding,” *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 40, no. 1, pp. 215–222, 2009, doi: 10.1007/s11661-008-9690-3.
- [6] M. Celina, A. C. Graham, K. T. Gillen, R. A. Assink, and L. M. Minier, “Thermal degradation studies of a polyurethane propellant binder,” *Rubber Chem. Technol.*, vol. 73, no. 4, pp. 678–693, 2000, doi: 10.5254/1.3547613.
- [7] S. Md Ani, A. Muchtar, N. Muhamad, and J. A. Ghani, “Binder removal via a two-stage debinding process for ceramic injection molding parts,” *Ceram. Int.*, vol. 40, no. 2, pp. 2819–2824, 2014, doi: 10.1016/j.ceramint.2013.10.032.
- [8] W. J. Tseng and C. K. Hsu, “Cracking defect and porosity evolution during thermal debinding in ceramic injection moldings,” *Ceram. Int.*, vol. 25, no. 5, pp. 461–466, 1999, doi: 10.1016/S0272-8842(98)00061-3.
- [9] K. S. Hwang and T. H. Tsou, “Thermal debinding of powder injection molded parts:

- Observations and mechanisms,” *Metall. Trans. A*, vol. 23, no. 10, pp. 2775–2782, 1992, doi: 10.1007/BF02651756.
- [10] D. Lin *et al.*, “Rheological and thermal debinding properties of blended elemental Ti-6Al-4V powder injection molding feedstock,” *Powder Technol.*, vol. 311, pp. 357–363, 2017, doi: 10.1016/j.powtec.2016.12.071.
- [11] E. S. Thian, N. H. Loh, K. A. Khor, and S. B. Tor, “Effects of debinding parameters on powder injection molded Ti-6Al-4V/HA composite parts,” *Adv. Powder Technol.*, vol. 12, no. 3, pp. 361–370, 2001, doi: 10.1163/156855201750537901.