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Recovery of Aluminum from Aluminum Coated Plastic Waste using Pyrolysis Process

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Abstract

This study aims to characterize the aluminum metal obtained from pyrolysis of aluminum coated plastic waste, to study the effect of temperature on the yield of total solids and aluminum, and to obtain the kinetic parameters of aluminum coated plastic waste pyrolysis. Prior to this study, plastic waste was cleaned, dried, cut, and carefully weighed as much as 100 grams per batch. The pyrolysis was carried out for 2 hours at a desired temperature and the reactor was let to equilibrate to room temperature. The volatile matters produced from pyrolysis was condensed and weighed every 10 minutes from the first drop until the end of the pyrolysis. The remaining solids in the reactor were collected, the aluminum was separated from the char and was subsequently melted, molded and cooled. Experiments were repeated in various pyrolysis temperatures (500, 550, 600 and 650°C). The results show that the increase of pyrolysis temperature decreases the yield of total solids, while the aluminum yield remains unchanged. The aluminum metal recovery was 5.3% w/w with purity of 95.80%. The most appropriate kinetic model to represent the pyrolysis of plastic waste is a single reaction model with the value of kinetic parameters of pre-exponential factor (A) 18.2689 min^{-1} and the activation energy value (E) 40.2310 kJ/mole.

Keywords: *aluminum; kinetic parameter; plastic wastes; pyrolysis; temperature*

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INTRODUCTION

As a result of the steady increase in world population, the basic needs required by people also increase accordingly, including food and beverages. In this regard, the amount of plastic as one of the most used food packaging materials will also increase and subsequently increase the production of plastic waste. Aluminum-coated plastic packaging is the most widely used type of packing for snacks. Aluminum content in the plastic packaging can be recovered so that plastic waste problems can be reduced. Aluminum metal is broadly used in various fields because it is light, strong, not magnetic, and non-toxic. In addition, aluminum is also corrosion-resistant, cheap, and recyclable. The recycled aluminum metal is very useful because it can be processed into other aluminum products so that it can help to fulfill aluminum needs. One of the utilizations of aluminum is as a building material in the form of alloy for the improvement of mechanical properties and microstructure of the aluminum. In its pure state, aluminum is too soft so that its strength is very low for uses in various technical purposes. Aluminum is used for roofs and walls in the form of corrugated sheets with medium strength and hardness (hardness of 30 brinnel materials), corrosion resistant, and lightweight (SNI 03-1583-1989)

As recyclable materials, plastic waste can be treated through a more environmentally friendly process to reduce the negative impact of conventional plastic waste handling processes. One of the alternative processes is pyrolysis, which allows recycling of plastics, including multilayer plastic containers, such as aluminum-coated plastics. Pyrolysis of plastics can be performed at low temperature (<400°C), moderate temperature (400-600°C), or high temperature (>600°C) under atmospheric pressure. The thermal decomposition of the plastic polymers produces gas, distillate, and char, in varying relative amounts. Pyrolysis products can be used as fuel, petrochemical, and other applications. The pyrolysis process involves the breaking of the molecular bond and is endothermic, so that the supply of heat becomes very important and usually determines the decomposition rate. This process is characterized by indirect heating of materials through furnace walls or pipes (Buekens, 2006).

One of the important factors affecting the pyrolysis process is temperature. At 400-600°C, the main components of the produced oil are naphtha, heavy oil, gasoline, diesel oil, and kerosene. Increased temperatures above 600°C will increase the gas product and light hydrocarbons (C1-C4), and consequently lowers the number of products with high carbon (C21-C30) (Xingzhong, 2006). Fast pyrolysis of plastic waste at temperatures from 500-800°C, produces a dark brown liquid as a main product, which is a mixture of gasoline, diesel, and heavy oils (Wiriyaumpaiwong and Jamradloeduk, 2017). At lower pyrolysis temperature, the product is dominated by wax and char remaining in the reactor. However, there are also liquid product (paraffin oil) and gas. Increasing the pyrolysis temperature can increase the amount of the liquid products and reduces of wax product (Achilias *et al.*, 2007). However, the liquid products will decrease after passing a certain temperature. In general, pyrolysis at approximately 500°C produces maximum amount of liquid products. Paraffin and olefin are the main components present in the liquid products. Paraffin yield decreases along with the increased temperature, while yield of olefin will increase and change into gas phase. This is because at temperatures above 550°C, the secondary cracking on compounds with 18 carbon atoms occurs. At low temperatures, heavy fractions will be formed with the number of carbon atom is C35 (Marcilla *et al.*, 2009).

Research on plastic pyrolysis has been widely practiced for both single plastic and mixed plastic. Most studies use non-coated plastic films, such as crackle bag (LDPE), beverage bottles (PET), HDPE, and others. Among these are Laksono (2014), Jamradloedluk and Lertsatitthanakorn (2014), Dewi (2014) and Lopez *et al.* (2010) who pyrolyzed LDPE, HDPE, PE and PS separately, and plastic mixture, respectively. Several studies use multilayer packaging plastics, including Korkmaz *et al.* (2009) and Undri *et al.* (2014) who pyrolyzed aluminum-coated beverage packaging. In addition, Rutkowski (2013) pyrolyzed beverage packaging containing paper and metal. In general, research has been done only to obtain pyrolysis products without further processing to process the resulting product, especially the solid product.

To obtain the kinetic parameters of plastic waste pyrolysis rate, several models of pyrolysis reaction mechanisms have been used. Model I is the simplest single chemical reaction mechanism, called as single step model. This model was once used in studying the kinetics of several biomass pyrolysis processes, among them are Kung (1972) and Fadhillah (2005). This model shows no competition of product formation. A single reaction mechanism is considered to represent a pyrolysis mechanism according to the general chemical reaction equation assuming the rate of oil, solid, and gas formation from plastic waste decomposition are equal.

$$\text{Plastic} \xrightarrow{k} \text{Oil + Solid + Gas} \tag{1}$$

This research proposes the second model (Model II), a pyrolysis reaction mechanisms that have been used in the pyrolysis of wood, called as one component mechanism. The used assumption is the rate of oil, solid, and gas formation is varied.

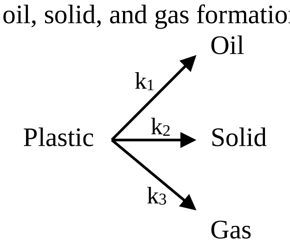


Figure 1. One component mechanism (Blasi, 2008)

Plastic mass balance (p):

$$\frac{dm_p}{dt} = -k_1 m_l - k_2 m_s - k_3 m_g \tag{2}$$

Oil mass balance (l):

$$\frac{dm_l}{dt} = k_1 m_p \tag{3}$$

Solid mass balance (s):

$$\frac{dm_s}{dt} = k_2 m_p \tag{4}$$

Gas mass balance (g):

$$\frac{dm_g}{dt} = k_3 m_p \tag{5}$$

This research aims to introduce a simple aluminum metal recycling technology, which is recovery of aluminum layer from plastic food packaging. The purposes of this research are to study the effect of temperature on the total solid and aluminum yields during plastic waste pyrolysis at atmospheric pressure and to find its kinetic parameter for the design of pyrolysis reactor.

MATERIALS AND METHOD

Materials and Equipment

The material used in this study was aluminum coated plastic (polyethylene and polypropylene) waste in the form of food packaging. The main equipment used was a batch pyrolysis reactor, whereas analytical instruments used included aluminum product composition test using metal scanning spectrometer (Arun metal scan, UK), microstructure test using metallographic microscope, (Nikon, Japan), hardness test using Brinnel portable hardness, and chemical composition test using X-ray fluorescence (XRF, PANalytical, UK).

Method

Aluminum-coated plastic trash was cleaned from dirt and washed using flowing water. Prior to pyrolysis, the clean waste was then dried and cut into smaller uniform size. As much as 100 gram of plastic waste was introduced into the pyrolysis reactor. The reactor was heated up from room temperature to reach the desired temperature (at 450°C) and the pyrolysis was left to last at constant temperature for 2 hours. The volatile matters coming out from the reactor was condensed and further referred as plastic oil. The weight of plastic oil was recorded every 10 minutes from the first drops to the end of the pyrolysis. The remaining solids (aluminum and carbon) in the reactor were collected after the completion of the pyrolysis process and the reactor had been cooled down to room temperature. The experiment was repeated at various temperatures (500, 550, 600, and 650°C). The aluminum and carbon residue in the solid products were separated. The aluminum was re-melted, molded, and cooled, then cut into several specimens for analysis.

RESULTS AND DISCUSSION

Characterization of Aluminum

The solid residues of pyrolysis of PE and PP plastic with aluminum coatings consist of aluminum and char. The higher the pyrolysis temperatures, the less carbon presents in the solid residue. Upon solid separation, it was observed that aluminum is recovered in the form of silvery thin sheets. Prior to treatment, carbon char was separated from the aluminum physically to remove the impurities. The amount of obtained solid from pyrolysis was up to 26% w/w of the initial plastic mass and the obtained aluminum product (aluminum costing) is 5.3% w/w. The chemical composition of plastic waste as raw material and the composition of the aluminum product are shown in Table 1.

The increase in aluminum content of the products, which shown in Table 1, is due to the separation of other elements of the plastic raw material in the form of oil, carbon char and gas. The isolated aluminum obtained in this study can be classified as aluminum alloy, Al-Si. Aluminum alloy containing 95.8% aluminum has a higher mechanical strength than pure aluminum due to the presence of other elements, such as Si and Cu. Based on hardness value, the aluminum alloy obtained in this study is classified in as medium hardness category (< 70 HB). With such hardness values, it can be used in a variety of engineering purposes, especially as a building material. The microstructure of the aluminum obtained from pyrolysis of plastic waste shown in Figure 2 indicates the presence of others elements, and being similar to the aluminum alloy microstructure (Figure 3). The bright matrix portion of the structure represents an aluminum solid solution.

Table 1. Chemical composition of aluminum coated plastic waste and aluminum product

No	Parameter	Composition (%)	
		Raw Material	Product
1	Al	77.57	95.80
2	Fe	2.38	0.719
3	Si	1.61	1.90
4	Cu	0.2	0.159
5	Others	18.24	1.722

Figure 2. Microstructure of aluminum product

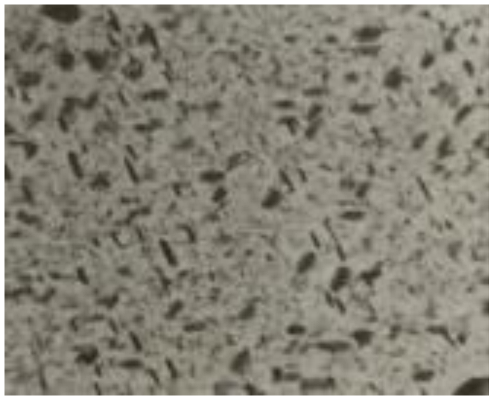


Figure 3. Microstructure of aluminum alloy Al-Zn-Cu-Mg-Zr (Callister, 2003)

Effect of Temperature on Solid Products

During pyrolysis, the plastic waste decomposes into oil and gas products leaving solid residue in the pyrolysis reactor, which contains aluminum. The yield of total solid and aluminum achieved at various temperatures are shown in Figure 4. In general, the solid produced from plastic waste pyrolysis in this study, consists of aluminum and carbon char. However, pyrolysis of plastic waste at 450°C also produced petroleum wax. The formation of wax indicates that pyrolysis at 450°C is still not sufficient to achieve a complete pyrolysis. At this temperature, only a small amount of volatile matters can be evaporated so that the rest will remains in the reactor. Figure 4 shows that a higher temperature resulted in a lower yield of total solid, while the aluminum yield is relatively constant in a range from 0.034 to 0.1. An investigation conducted by Korkmaz *et al.* (2009) also showed similar results in aluminum yields ranging from 0.069 to 0.07. The pyrolysis process conducted by Undri *et al.* (2014) produced aluminum of 7.3% (0.073).

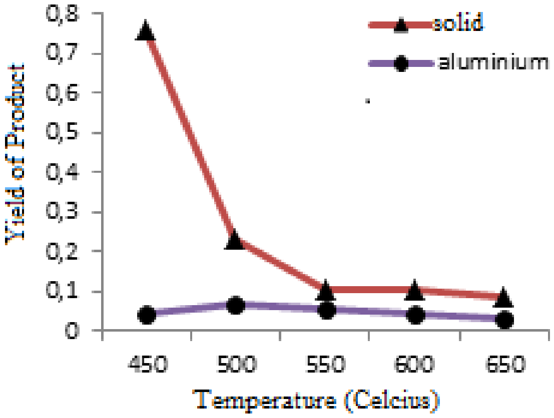


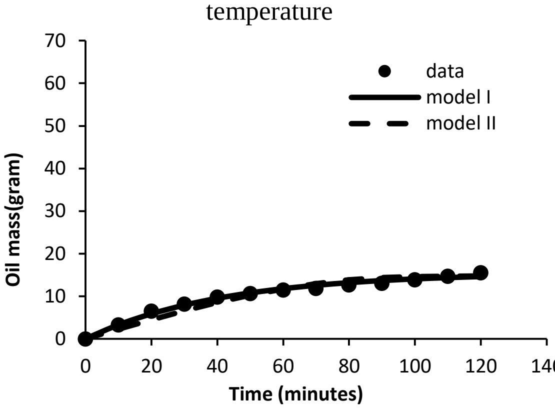
Figure 4. Yield solids and aluminum relationship to temperature

The total solid yields decrease along with the increase in temperature. This is due to faster and more intensive decomposition of plastic waste at higher temperatures. This is in accordance with the observation of Klass (1998) that the decomposition of a polymeric or high molecular weight compound will be more effective at higher temperature. According to Scheirs (2006), pyrolysis at a low temperature will increase the yield of the solid (char). In line with that finding, Marco *et al.* (2007), Korkmaz *et al.* (2009) and Undri *et al.* (2014) reported that solid yield decreased as pyrolysis temperature increased.

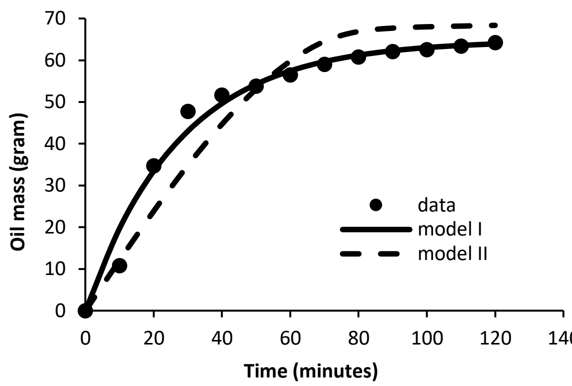
In aluminum-coated plastic pyrolysis, the solid residues comprise of aluminum metal and char of plastic waste. The reduction of amount of solid due to the increase in pyrolysis temperature can be interpreted by decreasing amount of carbon char in the total solid yield. At high temperatures, more gas and oil will be formed during pyrolysis. The smaller amount of carbon in the solid product indicates the presence of impurities. Aluminum with lower content of impurities will provide better quality. The presence of impurities in aluminum metal will affect its microstructure and mechanical properties as one of indicators of the quality.

Effect of Temperature on the Pyrolysis Process Rate

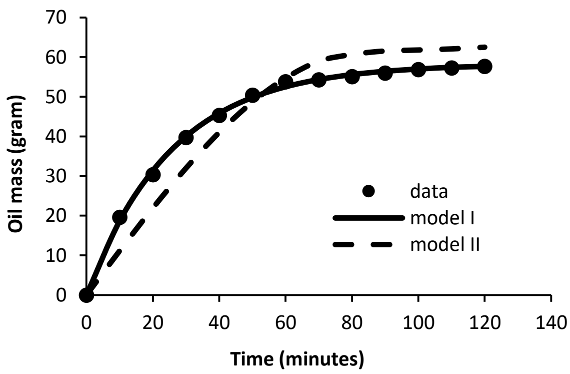
Figure 5 shows the correlation between the oil mass obtained from laboratory data at various times and the calculated oil mass from simulations using models I and II.



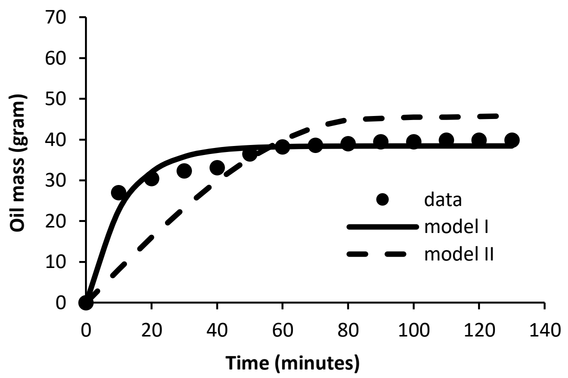
(a) 450ºC



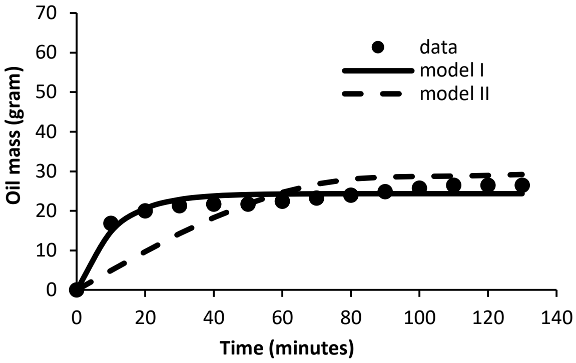
(b) 500ºC



(c) 550ºC



(d) 600ºC



(e) 650ºC

Figure 5. Mass relationships of oil data experiment and simulation model I and model II against time rate

Figure 5 shows that the simulation data is almost close to experimental data obtained from both model I and model II. Model I has the closest trend to the experimental data so it can be concluded that model I represents the mechanism of reaction of aluminum-plated plastic pyrolysis. This shows that plastics are decomposed directly into oil, solid, and gases simultaneously with the same reaction rate. The suitability of the reaction mechanism to model I is also indicated by the smaller error values compared to the error in model II, as shown in Table 2.

Table 2. Comparison of errors of model I and model II

Temperature	Error (%)	
	Model I	Model II
450	3.73	11.71
500	8.82	11.80
550	1.33	13.26
600	5.18	19.05
650	6.85	19.88
Average	5.18	15.14

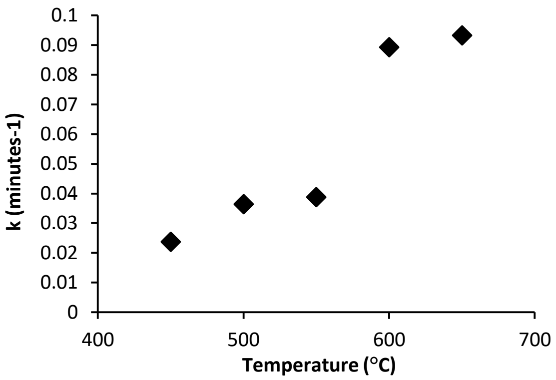


Figure 6. The relation between reaction rate constant and the temperature

The relation between reaction rate constant (k) and temperature is shown in Figure 6. Figure 6 show that a higher pyrolysis temperature will result a greater reaction rate constant (k) value. The reaction rate constant in this study is the overall reaction rate constant, which is obtained from the evaluation of the mathematical model of the pyrolysis reaction mechanism, using SSE optimization method by computer programming. The overall reaction rate is a function of temperature so that the value of k increases along with the increase of temperature. The values of k obtained at various temperatures can be used to calculate the kinetic parameters (pre-exponential factor and activation energy) in the pyrolysis reaction under assumption that Arrhenius Equation fit the effect of temperature:

$$k = A.e^{-\frac{E}{RT}} \quad (6)$$

The involved kinetic parameters (pre-exponential factor and activation energy) are searched by linearly equation 6 and the results are obtained in Figure 7.

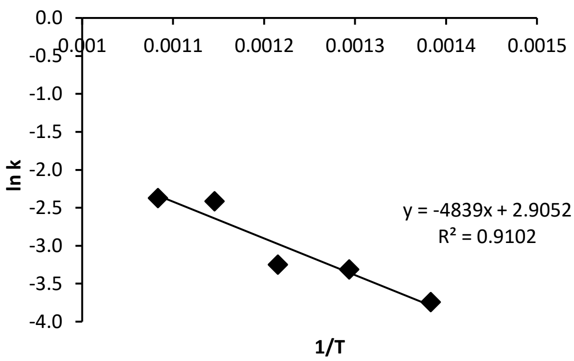


Figure 7. Relation between ln k and the 1/T

From Figure 7, a straight line relationship between ln k and 1/T can be obtained as represented by equation 7.

$$k = 18.2689\ exp\left(\frac{-4839}{T}\right) \quad (7)$$

From equation 7, the obtained value of parameter of pre-exponential factor (A) is 18.2689 min^{-1}, while the value of activation energy (E) is 40.2310 kJ/mole. The kinetic parameters which are obtained (A and E) are then used to calculate the new k value (k calculation). This calculated k value was further used to calculate the mass of the simulated oil (mass of calculation) in comparison with the experimental oil data shown in Figure 8.

Figure 8 shows a similar trend between the simulated oil yield and the experimental data. It can be said that the kinetic model assuming a single reaction mechanism is capable in describing the mechanism of the aluminum-plated plastic pyrolysis reaction with absolute error is 12.94%.

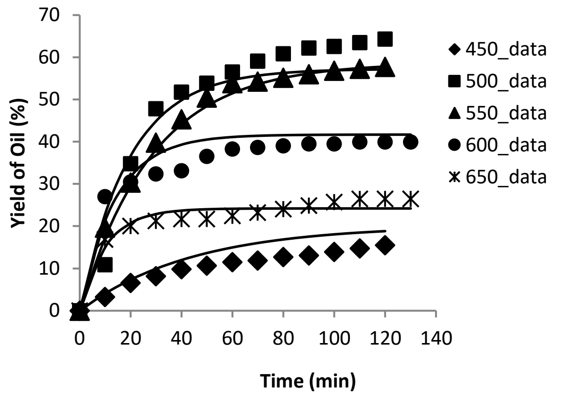


Figure 8. Relation of oil yield data and models against time at various temperatures

CONCLUSION

The obtained aluminum metal is 5.3% against the plastic mass with purity of 95.80% resembling hardness value of less than 70 HB. The increase of pyrolysis temperature will decrease the yield of total solids with almost constant aluminum yield. A rise in pyrolysis temperature will increase the rate of pyrolysis process with the rate constant following the equation $k = 18.2689\ exp\left(\frac{-4839}{T}\right)$.

NOTES

k : the overall reaction rate constant (without units)
k1 : the reaction rate constant of oil formation reaction (without units)
k2 : the reaction rate constant of the formation of solid reaction (without units)
k3 : the reaction rate constant of gas formation reaction (without units)
ml : oil mass (gram)
mp : plastic mass (gram)
ms : solid mass (gram)
mg : gas mass (gram)
t : time (minutes)

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