INVESTIGATION OF ELECTRON BEAM IRRADIATED POLYSTYRENE UNDER OVEN TREATMENT

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A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Hons.) Chemical Engineering

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DECLARATION

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

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **“INVESTIGATION OF ELECTRON BEAM IRRADIATED POLYSTYRENE UNDER OVEN TREATMENT ”** was prepared by **SOON ZHENG FOONG** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Chemical Engineering at Universiti Tunku Abdul Rahman.

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Supervisor : Ir. Dr. Lee Tin Sin

Date : ________________________________

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ABSTRACT

This study is aiming to investigate of mechanical, morphology, and thermal properties of electron beam irradiated polystyrene (PS) under oven treatment. Mechanical properties including tensile strength and Young’s Modules were seen to increase for low irradiation dose. Thus, PS irradiated with 150kGy electron beam possesses the higher mechanical properties. Meanwhile, PS irradiated with high electron beam dosages caused mechanical properties to degrade. During aging, the tensile strength and Young’s modulus were seen to be higher for irradiated PS aged at ramp conditions compared to constant aging for both 80℃ and 100℃. Hence, constant aging conditions caused more severely damages to PS. Differential Scanning Calorimetry (DSC) indicated that the bonding spectrum was narrower and the enthalpy of melting was higher when irradiated PS aged at ramp 100℃. By this analysis, ramp aged for irradiated PS at 100kgy possesses the better thermal properties. The morphology structure of the samples was observed and the Scanning Electron Microscopy (SEM) image suggested the elevated ramp aging temperature would increase the surface properties of irradiated PS depending on the dose of irradiation and aging days. Thus, ramp aged irradiated PS has better level of continuity of matrix than constant aged irradiated PS. In conclusion, the irradiated PS is stronger compare to pure PS due to the superior mechanical and thermal properties.

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LIST OF SYMBOLS / ABBREVIATIONS

ABS	Acrylonitrile-Butadiene-Styrene
CB	Carbon Black
PA 6,6	Polyamide 6,6
PB	Polybutadiene
PS	Polystyrene
sPS	Syndiotactic Polystyrene
EPS	Expandable Polystyrene
GPPS	General Purpose Polystyrene
HIPS	High Impact Polystyrene
LDPE	Low Density Polyethylene
LLDPE	Linear Low Density Polyethylene
PP	Polypropylene
iPP	Isotactic Polypropylene
HIPP	High Impact Polypropylene
NR	Natural Rubber
NR/R-EPDM	Natural Rubber/Recycled Ethylene-Propylene-Diene
DSC	Differential Scanning Calorimetry
SEM	Scanning Electron Microscopy
XRD	X-Ray Diffraction
TGA	Thermogravimetric Analysis
T_g	Glass Transition Temperature
T_m	Melting Temperature
T_c	Crystallization Temperature
T	Temperature

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CHAPTER 1

INTRODUCTION

1.1 Background

Plastics stand an important place in packaging industry (Roy, et al., 2006). Plastics are divided into two types, thermoplastic and thermosetting polymer. Thermoplastics are the most commonly used polymer in packaging industry as they have more distinct advantages such as ease of processing. They can be softened by heat and shaped over and over again to meet a variety of demand without altering the chemical composition. However, some polymers will have weaknesses such as brittleness, low glass transition temperature and low mechanical properties. For the last 25 years, advanced materials are required for a wide range of application including aerospace and automotives. These applications commonly required a unique combination of properties such as good mechanical properties, high heat tolerance and good adhesion.

Polystyrene (PS), which compose one of the major classes of synthetic polymers in the commercial use is one of the most commonly use thermoplastic. Because of its unique properties, PS has a wide range of applications ranging from packaging material to home installation. It is an amorphous, brittle and high molecular weight linear polymer (Gurman, Baier and Levin, 1987). PS is not resistant to aromatic, aliphatic, and chlorinated organic solvents but is resistance to biodegradation due to high molecular weight structural complexity. However, PS is thermal degradation which induce losses in it mechanical and tensile properties (Kiatkamjornwong, et al., 1999).

Modification and enhancement of the properties of polymer able to be done by conventional chemical or by exposure to electron beam irradiation. One of the potential directions in improving the performance of a polymer is by cross-linking using a high energy electron beam irradiation which produces a homogenous network (Dijkstra, Hoogsteen and Pennings, 1989). Important properties of polymer such as mechanical properties, chemical resistance and heat tolerance can be enhanced. Over the past 50 years, radiation cross-linking is one of the most accepted techniques in enhancing and modification the properties of polymer. This happens because electron beam irradiation is effective, faster, low cost and eco-friendly (Rao, 2009). It can be carried out at room temperature without the need of chemical catalysts, toxic chemicals or severe physical conditions such as high pressure. Therefore, in order to enhance the mechanical properties and heat tolerance of PS, exposing PS to high energy electron beam irradiation is a most simple and cost effectiveness way.

It is essential to confirm that the properties of the irradiated polystyrene match the requirement for designer and engineer using plastics. Thermal aging performance of irradiated PS can be test by putting sample in an oven for certain range of durations. In this case, the performance of polymer properties such as tensile strength, degree of crystallinity and elongation at break can be choose to monitor after heat aging. However, majority of the polymer have a long life after modified which takes years to get an assessable change. Thus, oven aging test is most commonly used to accelerate the aging process (Laurence, 2014).

Electron beam irradiation has more pros than cons for the development of high quality and high performance polymer properties which lead to the exponential growth of radiation processing. Thus, this electron beam irradiated PS may provide better performance than regular PS in term of heat tolerance and mechanical properties

1.2 Problem Statements

Polystyrene stand an important place in packaging industry due to its excellent physical properties, low production costs and wide range of applications. However, it is susceptible to thermal degradation which induce losses in it mechanical and tensile properties. This problem can be overcome by exposing PS to high energy irradiation which could improve the properties of PS. However, different dose of high energy irradiation would affect the properties of PS. Therefore, this study is to assess the effects of different dose of high energy irradiation on PS under thermal aging. The problem statements were showed in the following:

1. What are the mechanical properties, thermal properties and physical properties of irradiated PS under constant thermal aging?

2. What are the mechanical properties, thermal properties and physical properties of irradiated PS under ramp thermal aging?

1.3 Objectives

The main objective of this study is to assess the effects of different dose of high energy irradiation of polystyrene under thermal aging. This is to make polystyrene less susceptible to thermal degradation under hot environment.

1. To determine mechanical, thermal and physical properties of irradiated PS under constant thermal aging.

2. To determine mechanical, thermal, chemical and physical properties of irradiated PS under ramp thermal aging.

1.4 Scope of Study

This study is mainly focus on the oven treatment of the electron beam irradiated polystyrene. According to the objectives established previously, there were several technical tasks and analysis would be performed to characterize the irradiated polystyrene. All the characterization techniques and preparation of samples were shown in the following.

1.4.1 Sample Preparation

The pure polystyrene will be hot pressed into sheets of 1 mm × 15 cm × 15 cm by using a hot presser. The compound will be then cut into a dumbbell shape in according with ASTM D1822.

1.4.2 Sample Characterization

1.4.2.1 Mechanical Properties

The mechanical properties of the sample will be evaluated by tensile test, using Instron Universal Testing Machine 5582 (Model 4302 Series IX).

1.4.2.2 Thermal Properties

Differential Scanning Calorimetry (DSC) analysis of the sample will be carried out by using Mettler-Toledo DSC823E/200 analyzer.

1.4.2.3 Physical Properties

Scanning Electron Microscopy (SEM) analysis will be carry out by using JOEL JSM-3301F SEM.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Polystyrene

Polystyrene, a synthetic aromatic polymer produced by the addition polymerization of the styrene monomer unit, as shown in Figure 2.1 (Yousif and Haddad, 2013). The main process route to styrene is the direct catalytic dehydrogenation of ethyl benzene. Polystyrene is a genetic term, which symbolizes a number of forms such as crystal, impact and expandable form. Polystyrenes are amorphous with linear high molecular weights polymers (Gurman, Baier and Levin, 1987). PS is relatively inexpensive and is a homogeneous polymer. It is stable in the room temperature and has a glass transition temperature (T_g) between 90°C to 110°C (Samsudin, et al. 2006). It is a polymer widely used in our daily life.

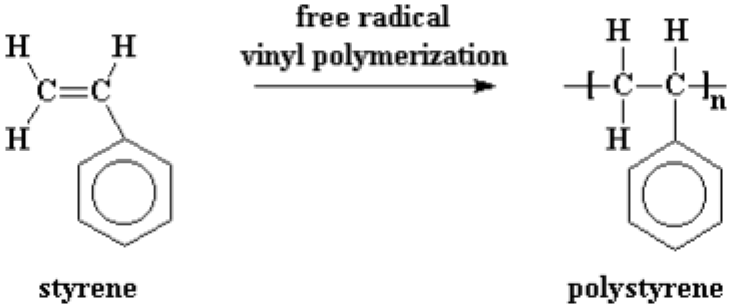


Figure 2.1: Polymerization of styrene to produce polystyrene (Yousif and Haddad, 2013).

2.1.1 Types of Polystyrene

There are three main types of polystyrene most commonly used in commercial. They are General Purpose Polystyrene (GPPS), High Impact Polystyrene (HIPS) and Expandable Polystyrene (EPS).

GPPS is a weather resistant, tough and brittle polymer. It is produced from styrene monomer which undergoes a process called suspension. GPPS commonly used as laboratory ware and disposable medical products. HIPS have improved features such as impact resistance, tensile strength and ease of processing. HIPS is produced by polymerization of a styrene polybutadiene solution. It is used in medical components and manufacture of tyres. EPS is a low density foamed polystyrene and has good toughness. EPS is produced by the addition of a blowing agent into polystyrene which expand the polymer chain. It is used as insulation in the building and packing material as cushion for fragile items.

2.1.2 Environmental Effects of Polystyrene

Polystyrene are resistance to biodegradation due to its hydrophobic nature and high molecular weight structural. These properties causes polystyrene cannot be decomposed by microorganisms for long period of time and hence cause environmental pollution. In addition, plastic recycling is not encouraged as the transportation of large volume of polystyrene waste is costly and makes recycling technique not viable.

Besides, incinerations are also not encouraging because incinerations of polystyrene will releases some harmful and toxic gases. Landfill method is also not an excellent method as dangerous gases will be gave off from landfill sites that cause local air pollution and contribute to global warming. Local streams could also become polluted with toxins seeping through the ground from the landfill site.

2.2 Types of Irradiation

In the past few years, radiation processing has been widely used to modify and improve the properties of polymers. Important properties such as mechanical properties, processability, melt flow index and thermal stability of polymer can be modified to suit its purpose by irradiate with different dose rate. There are various radiations sources such as X-ray, gamma radiation and electron beam radiation used for radiation processing. These radiations induce alteration in the molecular structure arrangement and macroscopic characteristics of polymers. As a result, crosslinking and chain scissioning occur due to the free radicals are produced when the energy from radiations is absorbed by polymer.

However, in radiation technologies gamma radiations and electron beam radiations are most commonly used. Table 2.1 showed the differences between gamma radiation and electron beam radiation. The major difference between two radiations is the dose rate. A gamma irradiator radiate approximately 10 kGy/h dose rate while electron beam irradiator radiates at a dose rate 100 kGy/s. The huge dose rate difference cause the irradiation times very much different. A gamma radiation would take several hours to deliver its dose while an electron beam radiator would only take seconds to deliver the same dose to the specimens. (Woo and Sandford, 2002)

Table 2.1: Comparison between gamma radiation and electron beam radiation (Woo and Sandford, 2002)

Characteristics	Electron Beam	Gamma rays (^{60}Co)
Energy (MeV)	0.1-20	1.3
Maximum penetration (cm)*	5.0	50
Dose rate	100 kGy/s	10 kGy/h
Charge	-1	0
Rest Mass	9.1×10^{-28} g	0
Velocity	0.3-0.99c	c**

2.2.1 Mechanical Properties

2.2.1.1 The Effects of Gamma Radiation on Mechanical Behaviour of Polystyrene

Albano, et.al, (2003), have done a research on the mechanical irradiated polystyrene at low doses and high doses. The research was carried out by exposing PS at different gamma irradiation dosage. According to earlier studies, at low doses of irradiation only small changes in the mechanical properties of polymer will be observed. In higher doses of irradiation, significant changes were observed from increasing of mechanical strength and then decreases when over certain dosages.

Both tensile strength and elongation at break of PS was showed in Figure 2.2(a) and Figure 2.2(b). From the result, tensile strength and elongation at break of PS increased 60% at integral doses from 70 kGy to 400 kGy, comparing to pure PS. The reason is because at integral irradiation dose from 70 kGy to 400 kGy crosslinking processes begin. However, at irradiation doses higher than 400 kGy, both tensile strength and elongation at break of PS dropped significantly. The significant decrease of PS mechanical properties is usually due to serious chain scissioning reaction occurring in PS. In conclusion, the results revealed that different polymers will have different optimal radiation dosage where the mechanical properties of polymer will improved to maximum due to crosslinking reaction and above the optimal radiation dosages the mechanical properties decrease significantly due to dominant of chain scissioning reaction occurs.

However, at integral doses from 0 kGy to 60 kGy, both tensile strength and elongation at break of PS remain. According to a research done by Dole (1977), PS mechanical properties such as tensile strength, elongation at break and Young’s modulus will be unaffected or affected slightly by low doses of irradiation. This is because the low dose of electron beam radiation was insufficient to induce an increase in the mechanical properties of PS. The high intermolecular force in PS tends to reduce changes in scission and crosslinking reactions during low doses of irradiation. Besides, at low dosage levels crosslinking most likely to occur at the crystal boundaries or the amorphous phase of PS. The Young’s modulus of a polymer depends mainly on the degree of crystallinity of polymer. The low irradiation dosage has no effect on the crystalline structure of PS. As a result the Young's modulus of PS remains unchanged compared to non-irradiated PS. Hence, the mechanical properties of PS are insensitive to low dose irradiation except at sufficient dosage to disrupt the phenyl ring and mechanical properties of PS deteriorated as showed in Figure 2.2(a) and Figure 2.2(b).

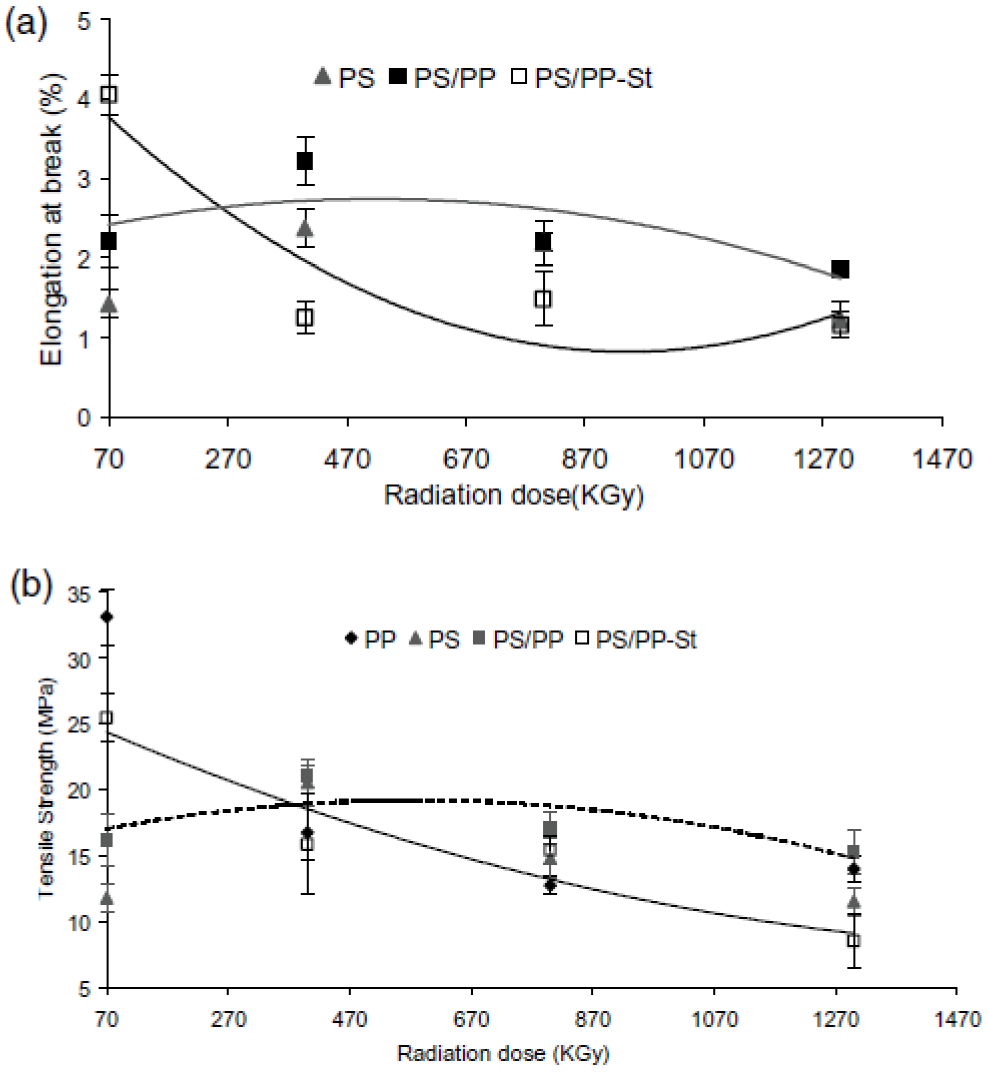


Figure 2.2: (a) Tensile Strength and (b) Elongation at Break behaviour of PP, PS, PS/PP-Styrolux, at different radiation doses (Albano, et al., 2003)

2.2.2 Thermal Properties

2.2.2.1 The Effects of Gamma Radiation on Melting Temperature of Polystyrene

In the earlier studies, done by Albano, et.al, (2003), have proved PS is one of the polymers that most stable against gamma irradiation. In other words, a large dosage of radiation is required to produce a noticeable change on the PS properties. The reason is because PS molecular structure consists of large amount of benzene ring which acts like a protective layer against radical-chemical process such as radiation. The melting temperature of PS was showed in Figure 2.3.

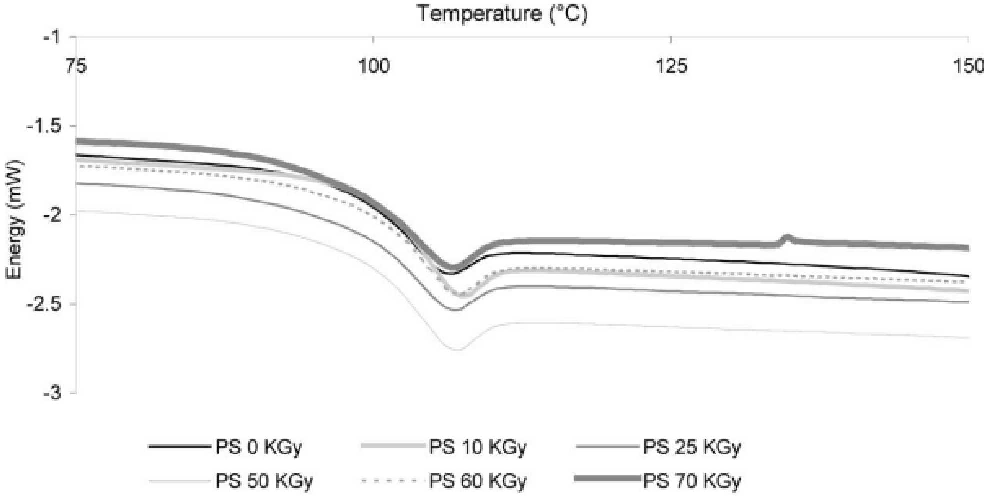


Figure 2.3: The effect of radiation on the DSC thermograms of PS at different integral doses (Albano, et al., 2003)

Figure 2.3 showed that the melting temperatures of PS at different doses remain in the range 107℃ to 110℃ . This shows the melting temperature of PS does not significantly affected by irradiation dose from 0 kGy to 70 kGy. Thus, in this case, it is said that the crosslinking reaction does not occur within the irradiation dose. The reason is because the crosslinking reaction is presence when melting temperature of PS increase significantly according to a research done by Chipara (1997). Besides, Charlesby (1957), has done a research and proved that to cause crosslinking reaction occur in PS, the radiation dose must be equal or greater than 250 kGy. This is due the protective action of PS benzene ring cause PS resistance to low doses of irradiation as mentioned earlier. Besides, the high intermolecular force of PS was also one of the factors that increased the resistivity of PS towards radiation. The resistivity effect from the high intermolecular forces of PS causes difficulty for crosslinking reaction to occur and thus only small changes of melting temperature.

2.2.2.2 The Effects of High Energy Electron Beam Radiation on Thermal Behaviours of Low Density Polyethylene

Murray, et al., (2012), also have done a research on the effects of high energy electron beam irradiation on the thermal behaviours of low density polyethylene (LDPE). The research was carried out by exposing LDPE to electron beam radiation at dosage of 25 kGy, 50 kGy, 75 kGy, 100 kGy, 150 kGy, 200 kGy and 400 kGy.

From Table 2.2, it was revealed that there were slight differences for melting temperature, heat of crystallization and percentages of crystallinity of LDPE samples which were treated at different irradiation dosages. From Table 2.2 the melting temperature of LDPE decreases a little with an increase in irradiation dose. This could be explained with the chain branches of LPDE which tends to reduce the thickness of crystallites. According to a research done by Puig, et al. (2010), it was concluded that electron beam radiation will cause changes in macromolecules of LDPE due to the presence of free radical reactions such as crosslinking and chain scissioning. As a result, branching in LDPE happen which in turn affect the melting temperature of LDPE. Besides, the amorphous region of LDPE which radicals were well distributed in this area will sensitive to radiation and as a result the crosslinking reaction will be promoted. Hence, the molecular weight between two crosslinked junctions decreases and causes the formation of imperfect crystalline. In conclusion, the melting temperature of LDPE was lowered.

From Table 2.2, it also showed that the crystallization temperature and percentage of crystallinity of LDPE decreases with an increase in irradiation dose. One of the main factors contributing to the decreases in crystallization temperature of

LDPE is the crosslinking network in LDPE structure as a result from electron beam irradiation. The networks cause the macromolecular chains unable to crystallize which interrupt the molecular order and put a stop to the growth of crystal. Besides, the heat of crystallization (ΔH), which is illustrated in Table 2.2 indicates that the crystallization of broken chains may be suppressed to some extent by the network structure. Thus, the changes in ΔH of LDPE decrease with the increasing of crosslinking density. As results, the percentage of crystallinity decreases as shown in Table 2.2.

Table 2.2: Melting temperature (T_m), crystallization temperature (T_c), and crystalline of the LDPE, before and after electron beam irradiation. (Murray, et al., 2012)

Sample dosage (kGy)	H_m (J/g)	Peak T_m, ℃	Peak T_c, ℃	% crystallinity	Crystalline degree variation (%)
0	83.40	113.01	102.84	28.83	0.00
25	81.38	113.12	102.40	28.13	2.42
50	82.04	112.72	101.99	28.36	1.63
75	82.43	112.59	101.63	28.49	1.16
100	82.77	112.37	100.58	28.61	0.76
150	76.59	111.67	100.41	26.47	8.17
200	78.24	111.32	99.40	27.04	6.19
400	79.08	109.24	96.94	27.33	5.18

2.2.2.3 The Effects of Electron Beam Radiation on Thermal Stability of Natural Rubber/Recycled Ethylene-Propylene-Diene Rubber Blends

A research has done by Nabil and Ismail, (2013), to studies the effect of electron beam irradiation on thermal stability of natural rubber/recycled ethylene-propylene-diene rubber blends (NR/R-EPDM). The samples were irradiated with different radiation doses, 50 kGy, 150 kGy and 200 kGy, respectively. Now, the thermogravimetric analysis was carried out by putting samples in a thermal analyser, scanned from 30°C to 600°C at a rate of 20°C/ minutes.

From Figure 2.4, it was observed that all curves follow a similar pattern and show two stages decomposition. From the figure, it showed that the initial minor weight loss happened at around 180°C to 200°C due to the presence of a volatile mater such as stearic acid and adsorbed water. The first stage of degradation of the blends was observed began at 330°C tand was completed at around 450°C as the natural rubber segment degraded. The degradation of natural rubber segments is susceptible to the presence of an oxidised structure and depletion of sulfidic crosslinking in the natural rubber. The second stage of degradation occurred at temperature range 450°C to 520°C due to the scissioning reaction of cross-linked R-EPDM network and conjugated natural rubber that remained after the first stage of degradation. From the figure, it also revealed that the thermal stability of blends increased with an increase in electron beam irradiation dosage. The increment in thermal stability of irradiated blends is due to the formation of more compact three dimensional cross-linked networks, which is more stable than the degradation layer formed. Besides, the decomposition temperature also shifted to a higher temperature towards irradiation dose which proved that the thermal stability of NR/R-EDPM is significantly improved. The reason is because of the formation of additional crosslinking in blends at higher irradiation doses. Thus, a higher temperature is required to break the crosslinking networks.

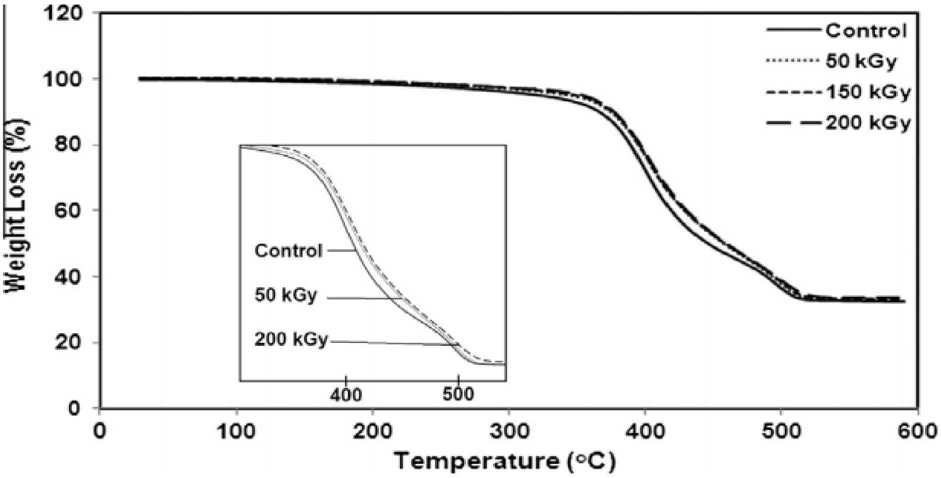


Figure 2.4: Thermogravimetric plots of NR/R-EPDM blends after irradiation doses of 50 kGy, 150 kGy and 200 kGy (Nabil and Ismail, 2013)

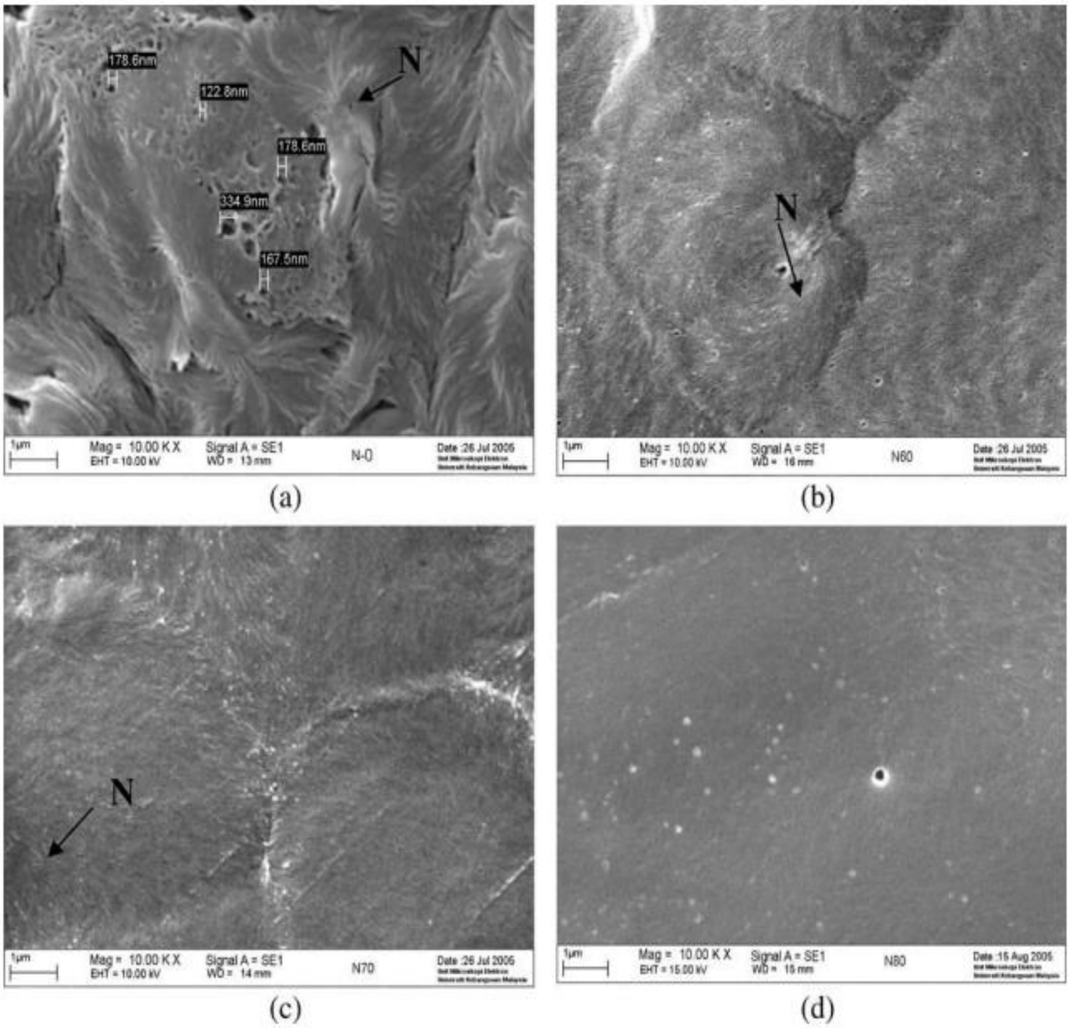
2.2.3 Physical Properties

2.2.3.1 The Effects of Electron Beam Radiation on Morphology Behaviour of Nylon-6,6

Amilia, Abdul and Zulkafli, (2009), have done a research on the effect of electron beam irradiation on morphology of nylon-66 membranes. The research was carried by radiate nylon-66 with electron beam at 60 kGy, 70 kGy and 80 kGy at 10 kGy per pass. The following Figure 2.5 showed the surfaces of non-irradiated and radiated nylon-6,6.

From Figure 2.5 (a), it showed that a non-irradiated nylon-6,6 surface obviously exhibited a spherical semicrystalline structures. This structure was very porous with branched crystals as seen from Figure 2.5 (a). As results, the structure could not hold water or salt solutions. By comparing Figure 2.5 (a) to Figure 2.5(d), it could be seen that the crystal structure was not same at different irradiation doses. The surface of nylon-6,6 becomes denser and less porous with increasing of irradiation doses. The reason is because crosslinking reaction occur during radiation which changes the surface become denser and form a three dimensional network. As a results, the porous size decreases. In this case, the presence of crosslinking reaction was proofed from the increases of gel content and declinations of degree of swelling in water. A research done by Krajewski and Oleich, (1995), on crosslinking sample membranes also have reported that the pore sizes of membranes and water absorption decreases with increasing of crosslinker concentration.

Nylon-6,6 is an opaque polymers due to radiate light at the spherical semicrystalline structures scattered. In this research, the radiation also changes the appearance of nylon-6,6 from an opaque surface to transparent, showed in Figure 2(d). The reason is because the radiation destroyed the spherical semicrystalline surface of nylon-6,6 and as a result the surface became transparent.



(a) (b)

(c) (d)

Figure 2.5: SEM image of non-irradiated and irradiated Nylon-6,6: (a) non-irradiated Nylon-6,6, (b) 60 kGy irradiated Nylon-6,6, (c) 70 kGy irradiated Nylon-6,6, (d) 80 kGy irradiated Nylon-6,6 (Amilia, Abdul and Zulkafli, 2009).

2.2.3.2 The Effects of Electron Beam Radiation on Crystallinity of Syndiotactic Polystyrene

Liu, et al, (2009), have done a research on the effect of gamma radiation on melting and chemical behaviours of syndiotactic polystyrene (sPS). The effects which were caused by crystallization time can be observed by using X-Ray Diffraction (XRD) analysis. The sPS were radiated with gamma radiation at a dose rate of 0 kGy, 200 kGy, 400 kGy, 600 kGy, 800 kGy and 1000 kGy in vacuum and oxygen, respectively.

The non-radiated and radiated sPS will be heated up to melt temperature, T_m, at 310℃ and then cooled down to crystallization temperature, T_c, in the 220℃ to 260℃. The samples were put into the X-Ray diffraction for analysis. Figure 2.6, showed the X-Ray diffraction results of isothermally crystallized sPS specimens which were irradiated in vacuum and oxygen environment. X-Ray Diffraction analysis is a test to illustrate the crystalline structure of polymer where the peaks represent the types of crystal or bonding present in the polymer after irradiation.

From the figure, it could be observed that a mixture of α phase and β phase structure were presence in both non-radiated and irradiated sPS despite of the atmosphere of radiation and radiation dosages level. However, the α peak intensity of non-radiated is a lot higher than β peak intensity. This deduced that a combination of α phase and β phase crystal structures will be produced at a melt temperature range from 300℃ to 340℃ while only α phase crystal structure will be produced at temperature below 230℃. From Figure 2.6(b), it showed that in oxygen environment, the radiation dose has a strong impact on the intensities of both α peak intensity and β peaks intensity. As example, the α peaks intensities at 6.7°, 11.6° and 15.6° decreases with increasing of irradiation dosages whereas at 12.3° the β peak appear to increase.

Besides, from the figure it was also observed the intensity of α and β peak increases at low irradiation and shaper comparing to α and β peak at high irradiation. The reason is because at low irradiation, the degree of crystallinity of sPS structure increases while at high irradiation, the degree of crystalline decreases. Thus, sPS is said to move towards crystalline state at low irradiation and at high irradiation the structure of sPS is distorted (Singh et al, 2010).

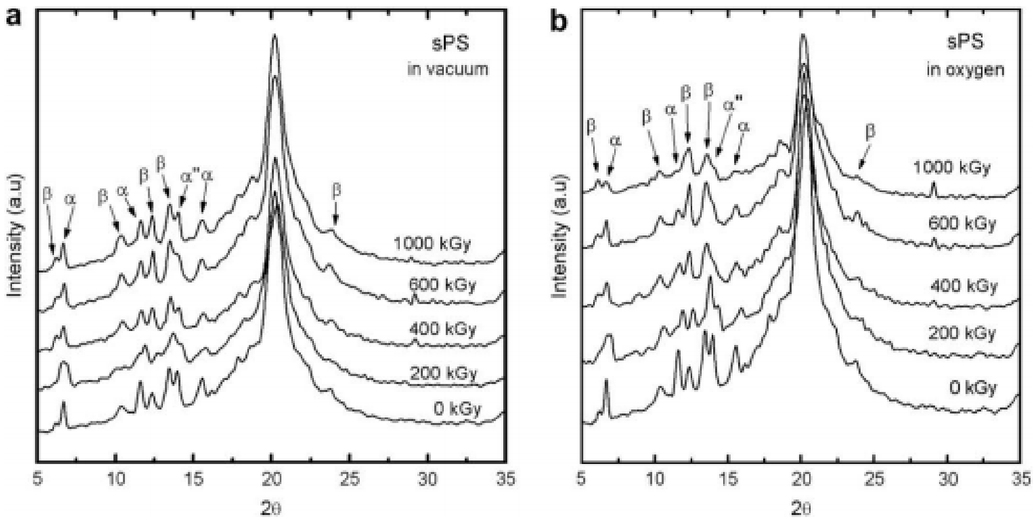


Figure 2.6: X-Ray Diffraction results of isothermally crystallized gamma irradiated sPS at different radiation dosages level: (a) irradiated in vacuum, (b) irradiated in oxygen. (Liu, et al., 2009)

In addition, Riquet, et al., (2013), also have done a research on the effect of radiation on properties of polypropylene (PP). The samples were put into the X-Ray diffraction and comparing the pattern of virgin PP with irradiated PP. Interestingly, the exposure of PP to electron beam caused a slight increment in the relative content of β crystal form. The reason is because the chain scissioning reaction dominates crosslinking reaction during electron beam irradiation and consequently these short chains reorganized themselves into crystalline structure (Sen and Kumar, 1995).

2.3 Thermal Aging Testing

In the past few years, thermal aging tests have grown popular in industrial application for testing of polymer, especially rubber polymers. There are two most commonly used aging oven in recent year which are cell ovens and cabinet oven. Cell ovens have been used for a long period of aging on polymer where a steady temperature could be achieved. Cabinet ovens are known as drying oven and are divided into two categories, with or without a fan. Ovens without a fan usually would have huge variations of the temperature in the space, up to 10°C particularly when the throttle of oven is open for an air exchange. Now, ovens with a fan would provide more precise results as ovens with a fan could provide a uniform temperature even at low at speed. These ovens are usually used in the polymer industry to test the performance level and lifetime of polymers.

Oven aging is used often to accelerate the aging process if polymer materials are formulated for long lasting life. The reason is because polymer with long lifetime would take years to test the polymer properties with a measurable change. Thus, by the end of aging the performance of polymer can be monitored through polymer properties such as tensile strength, stiffness and elongation at break

2.3.1 Mechanical Properties

2.3.1.1 The Effects of Thermal Aging on Mechanical Properties of Acrylonitrile-Butadiene-Styrene

Tiganis, et al., (2002), have done a research on thermal aging effect of acrylonitrile-butadiene-styrene (ABS). The research was carried out by aged ABS in the form of tensile specimens in an oven. The specimens were aging continued for 672h at 80℃, 90℃, 105℃, 110℃ and 120℃. The samples were removed periodically to test the mechanical properties of the aged ABS.

From Figure 2.7, the Young’s modulus of aged ABS at temperature 90℃ and 120℃ was showed. From the Figure 2.7, it was observed that Young’s modulus of aged ABS at 120℃ increases 40% comparing to ABS aged at 90℃ which has only slight increment. The significant increase is strongly depends on the changes of the surface structure of ABS during aging The reason is because during thermal degradation of ABS in the presence of oxygen the polybutadiene phase (PB) in ABS is caused by hydrogen extraction from carbon atoms from an alpha position,∝, to carbon-carbon double bonds. As a result, radicals such as carbonyl and hydroxyl were formed which promote crosslinking reactions and form degradation layer. The degradation layer creates an enhancement in Young’s modulus at the ABS exterior and enhanced the brittle failure. Hence, cracks will easily to be initiated in this degraded layer when load is applied and causing bulk failure due to rapid propagation of cracks. Besides, from Figure 2.8, it was observed that load of aged ABS at 90℃ decreases before failure. In contrast, for ABS aged at 120℃, the load drop is eliminated and failure takes place in the elastic region.

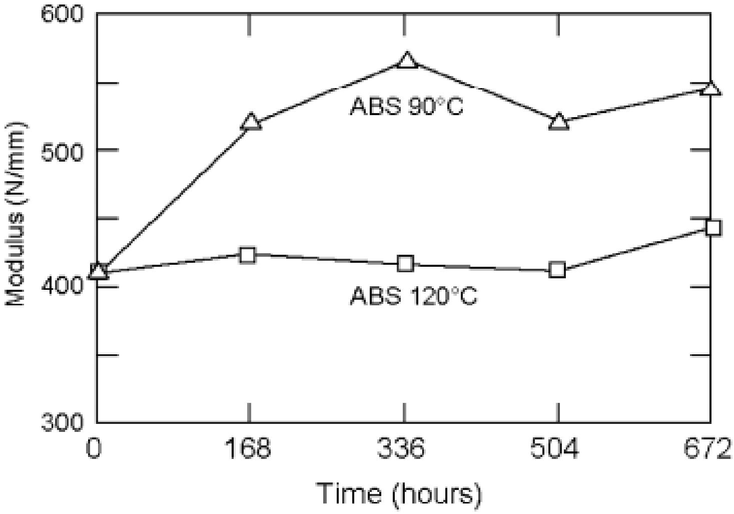


Figure 2.7: Young's modulus of aged ABS at temperature 90℃ and 120℃ (Tiganis, et al., 2002)

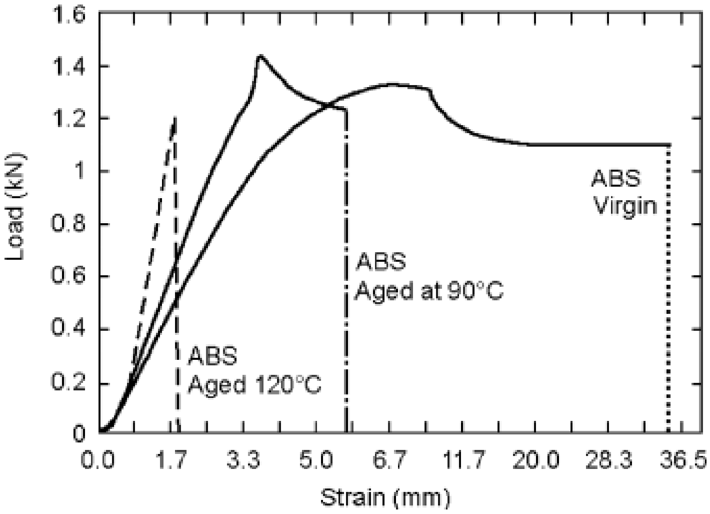


Figure 2.8: Stress-strain curve of virgin ABS and aged ABS at temperature 90℃ and 120℃ (Tiganis, et al., 2002)

2.3.1.2 The Effects of Thermal Aging on Mechanical Properties of Irradiated Natural Rubber/Recycled Ethylene-Propylene-Diene

Another research done by Nabil and Ismail, (2014), were to determine thermal aging properties of irradiated natural rubber/recycled ethylene-propylene-diene rubber blends (NR/R-EPDM) at different radiation dosage. The samples were irradiated by electron beam radiation at 50 kGy, 100 kGy, 150 kGy and 200 kGy. The irradiated samples were put into an oven with a fan at a temperature 100℃ for 48 hours. The samples were then tested with a tensile machine.

From Figure 2.9, it was revealed that the tensile strength of un-aged NR/R-EPDM exhibited optimum strength at irradiation dose of 50 kGy and reduced continuously at irradiation dosage above 50 kGy. In this case, the cosslinking promoter makes use of the free radicals formed during radiation to generate crosslinking network which cause tensile strength increase. However, when the blend samples were irradiated at dosage above 50 kGy more crosslinking network formed in the blend molecular structure which restrained the chains from structural arrangement during elongation. Thus, the tensile strength was reduced. Besides, a rubber will deformed externally when the crosslinking density is too high and fraction of the applied energy will be kept elastically in the chains and existing as a driving force for fracture. The left over energy is released through molecular motions into heat energy and is completely difficult to fracture further chains. Hence, at high crosslinking density chain motions become limited and the tight network is unable to releasing much energy which causes a decrease in tensile strength (Rooj, et al., 2014).

In addition, Figure 2.10 showed that the elongation at break of irradiated blends reduced continuously with the increase of electron beam irradiation dosage. The reason is because the chains between molecules and entanglements were breakdown which causes the ductility of blends samples decreased. Besides, the blends also became increasingly brittle as a consequence of the increase in crosslink density with irradiation (Ratnam, et al., 2001). Thus, tensile modulus and hardness property is believed to increase.

Furthermore, it was also observed that both tensile strength and elongation at break of all thermally aged blends decreased upon thermal aging. The reason is because of the oxidation reaction of the blend which resulted in either chain cleavage leading to a drop in molecular weight or crosslinking. Besides, the retained tensile strength at an irradiation dose of 50 kGy dropped slightly before increasing steadily with the increases of irradiation doses. Therefore, the crosslinking is enhanced by introduction of electron beam irradiation. Generally, the radical termination occurs after thermal aging of rubber which involved with the abstraction of hydrogen atoms from an allytic position on the rubber molecule. However, this process has already occurred after electron beam irradiation and the radical termination in the bulk polymer is no longer exists. So, during thermal aging, the Young’s modulus and tensile strength of blends reduced significantly compared to the control blend. Elongation at break showed higher retained properties than the control blend after electron beam irradiation dose. It could be concluded that the flexibility or elasticity of the blends is enhanced by electron beam irradiation and therefore increases the elongation at break.

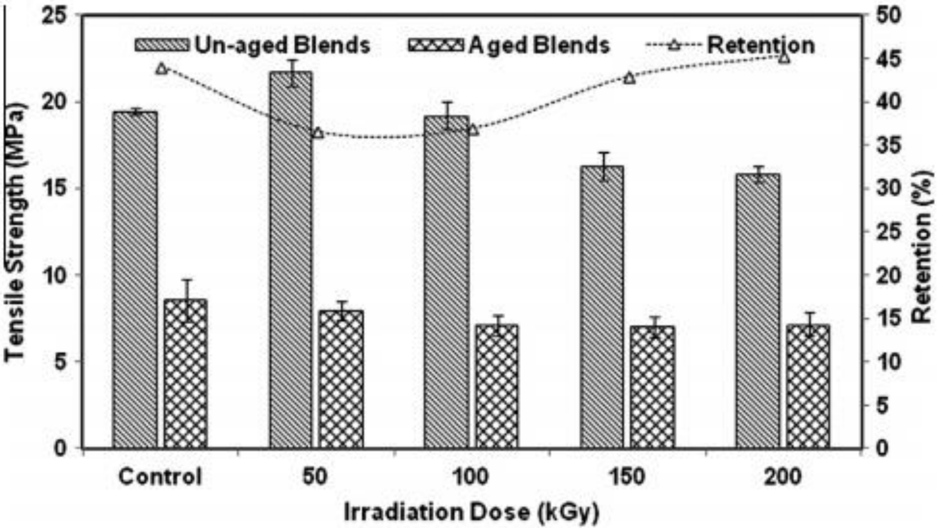


Figure 2.9: Tensile Strength of un-aged and aged NR/R-EPDM blends at different electron beam irradiation dosage (Nabil and Ismail, 2014)

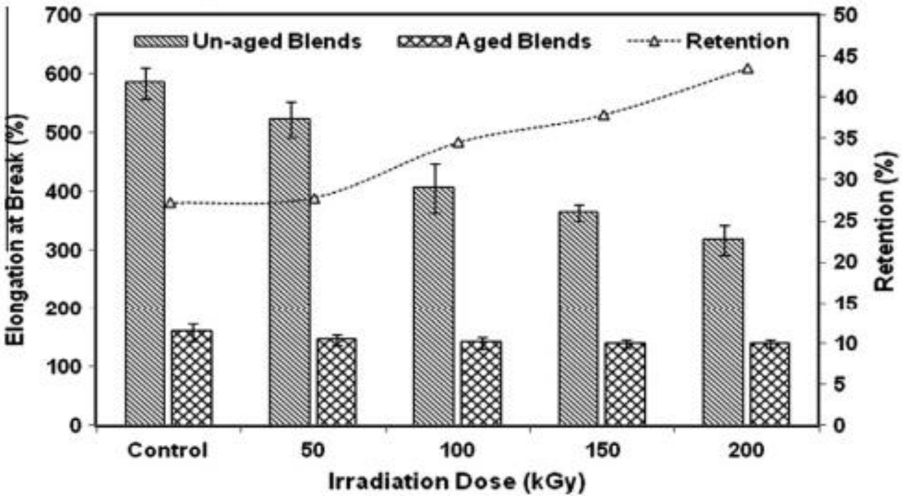


Figure 2.10: Elongation at break of un-aged and aged NR/R-EPDM blends at different electron beam irradiation dosage (Nabil and Ismail, 2014)

In another research done by Spetz, (1996), where natural rubber (NR) were put at three different temperature, 95℃, 100℃ and 105℃ in an oven for 168 hour. This research was done to determine the effect of thermal aging on the tensile properties of polymer. The results for NR are showed in Figure 2.11. From the figure, it was observed that the tensile strength and elongation of NR decreases with increases the temperature of oven. The reason is because the high temperature in oven cause interactions between free radicals and oxygen from the air and lead to chain scission reaction occurs.

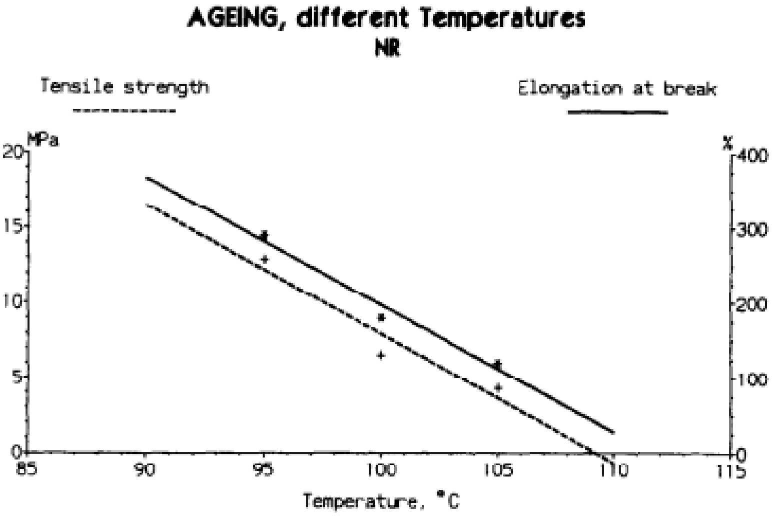


Figure 2.11: Tensile strength and elongation at break of natural rubber (NR) at different aging time (Spetz, 1996)

2.3.2 Thermal Properties

2.3.2.1 The Effects of Thermal Aging Time on Melting Temperature of Pure Polyamide 6,6

Cerruti and Carfagna, (2010), have done a research on the effects of thermal aging time on melting temperature of pure polyamide 6,6 (PA 6,6). PA 6,6 samples were put into a forced air oven at 110℃ and subjected to thermal oxidative degradation for 7000 hours. Figure 2.12 presents the DSC thermograms of PA 6,6 aged at 110℃ for different time of periods.

From the figure, it was observed that the incidence of the oxidative degradation was proved by a decline in the melting temperature and the form of a lot broader melting peak for harshly degraded samples. It was noted that short thermal aging times, 432 hours, caused melting temperature increased and an extremely sharp melting peak is observable. Additional aging causes a stable decline of melting temperature whose extend is around 20℃ after 7000 hours of thermal aging.

The early increment in melting temperature at 432 hours is linked to thermal annealing of polymer that enhances the degree of flawlessness of the crystals structure and support crystalline phase aggregation. For aging time above 432 hours, it was observed melting temperature of PA 6,6 decreased and melting curve were broadened. The reason is because the harsh thermal oxidation causes the development of a robustly degraded crystalline part which has a lower molecular weight and an obviously decreased melting temperature. As showed in the figure, the melting peak of PA 6,6 dropped to 140℃.

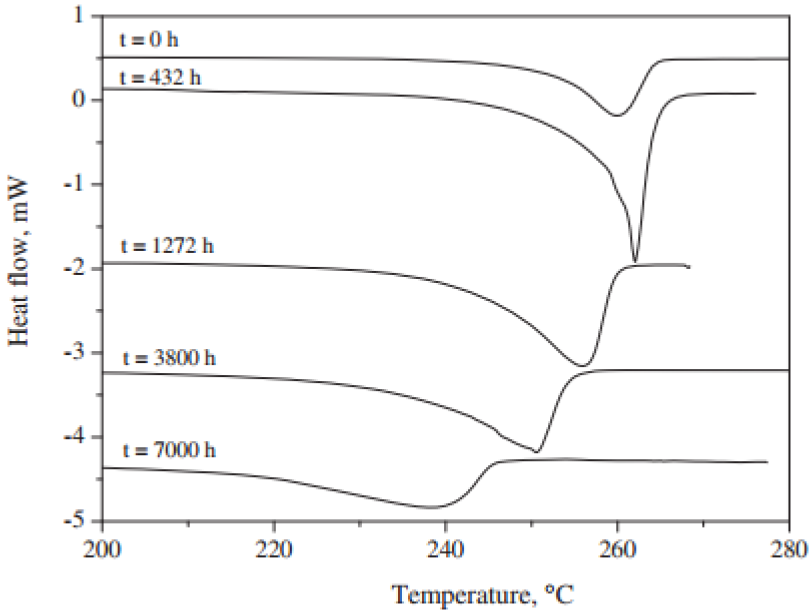


Figure 2.12: DSC thermograms of PA 6,6 aged at 140℃ for different time periods (Cerruti and Carfagna, 2010)

2.3.2.2 The Effects of Thermal Aging Time on Melting Temperature and Thermal Decomposition Behaviours of Linear Low Density Polyethylene

Weon (2010) has done a research on the effects of thermal aging on thermal properties of linear low density polyethylene (LLDPE). The samples were put into oven and subjected to thermal aging at temperature 100℃ for 720 hours, 2400 hours, 6000 hours and 7200 hours. A control sample exclusive of thermal aging was prepared to compare with aged samples. The crystallization behaviours of controlled sample LLDPE and aged LLDPE samples were measured using a DSC instrument. Thermogravimetric analysis was performed to study the thermal degradation and decomposition of unaged and aged LLDPE. Figure 2.13 showed the DSC thermographs of controlled LLDPE and aged LLDPE samples while Figure 2.14 showed the thermal decomposition behaviours of controlled LLDPE and aged LLDPE. The thermal decomposition was stated in terms of temperatures of 5% and 10% decomposition of each sample.

From Figure 2.13, it was revealed that thermal exposure time has a strong impact on the melting temperature, crystallization temperature and weight of crystallinity of LLDPE. It showed that the sample aged melting temperature and crystallization temperature increased 5℃ when subjected to thermal aging at 100℃ for 7200 hours. The reason is because of LLDPE chain chemistry and structure cause chain arrangement can easily be accomplished. Besides, a small endothermic peak was observed at temperature 115℃ for aged LLDPE at 6000 hours and 7200 hours. There are two types of endotherms was frequently observed. The first one is a large endotherm which occurred at high temperature (T1) while the second is a small endotherm occurred at low temperature (T2). T1 usually is associated to the crystallization of polymer chains which has high molecular weight and little branching while T2 is connected with crystal phase which has low molecular weight and high branching. From Figure 2.13 it showed that T2 endotherm was appeared in the aged LLDPE. The reason is because during thermal degradation, an intermediate crystal phase was formed. Compared to T1, T2 is less thermally stable and more branched in the thermally aged polymers.

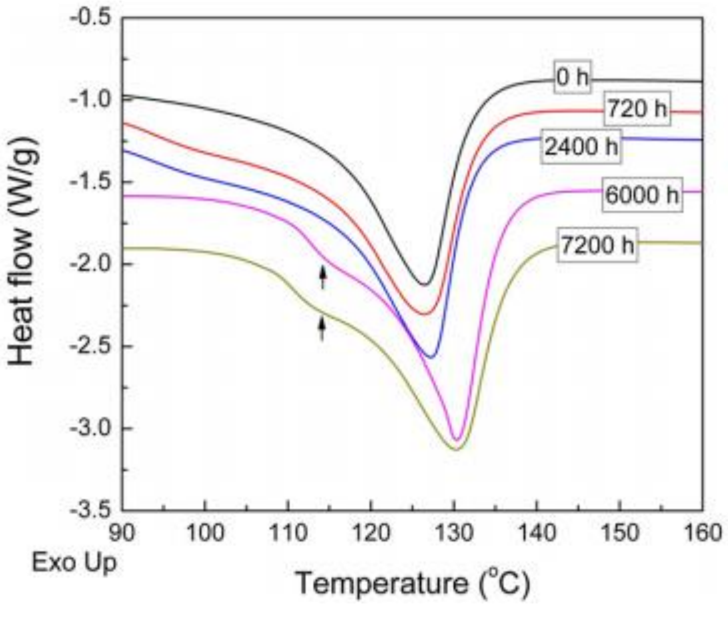


Figure 2.13: The effect of thermal aging on the DSC thermograms of LLDPE at different time, the endotherm of T2 was indicated with arrows (Weon, 2010)

From Figure 2.14, it was observed that TGA curves are single-stage mass decrease curve. The TGA curves show a therml decomposition step in the temperature range of 425℃ to 500℃. From the figure, both temperatures of 5% and 50% decomposition were observed increased with thermal aging times. The reason is because crosslinking reaction occurred and crosslinking density in the aged LLDPE increased.

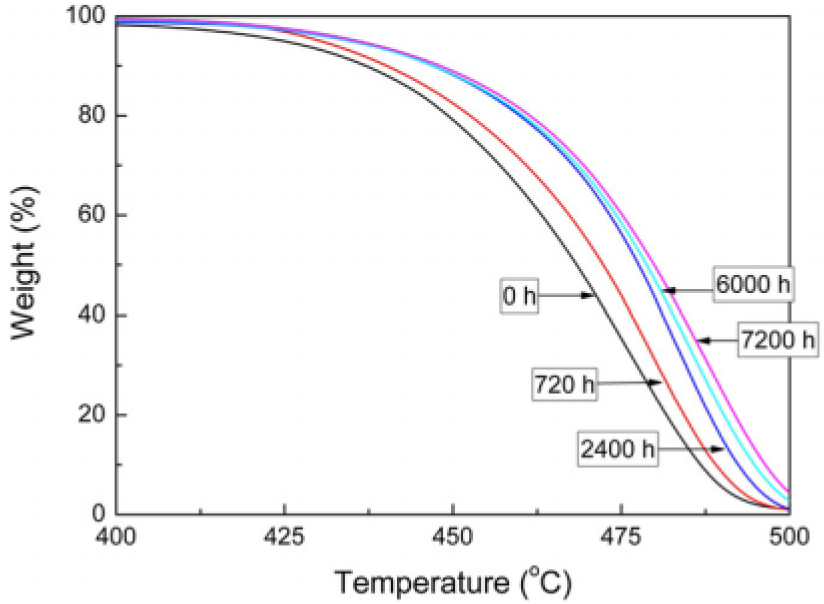


Figure 2.14: Thermogravimetric plots of thermally aged LLDPE (Weon, 2010)

2.3.3 Physical Properties

2.3.3.1 The Effects of Thermal Aging Time on Morphology Behaviour of High Impact Polypropylene

Chen, et al., (2007) have done a research to identify the effects of thermal aging on the phase morphology of high impact polypropylene (HIPP). HIPP samples were put in an oven for heat treatment at 200℃ for a series of time, 10 minutes, 30 minutes, 100 minutes and 200 minutes. Figure 2.15 presents the morphology of HIPP after heat treatment at 200℃ for a series of time.

From the figure, it showed that at heat treatment time of 10 minutes, the particles was well dispersed with a rapidly increases of the average size and the size distribution becomes boarder. The particles in the morphology were to be more or less spherical. However, the average size and size distribution reaches a stabilization stages after heat treatment for 30 min and most of the particles shape become more regular. With the increasing of heat treatment times, it could be revealed that the interparticle distance decreases and morphology become unstable. So, the results stated that reorganization the phase morphology takes place during thermal treatment (Chen, et al, 2007).

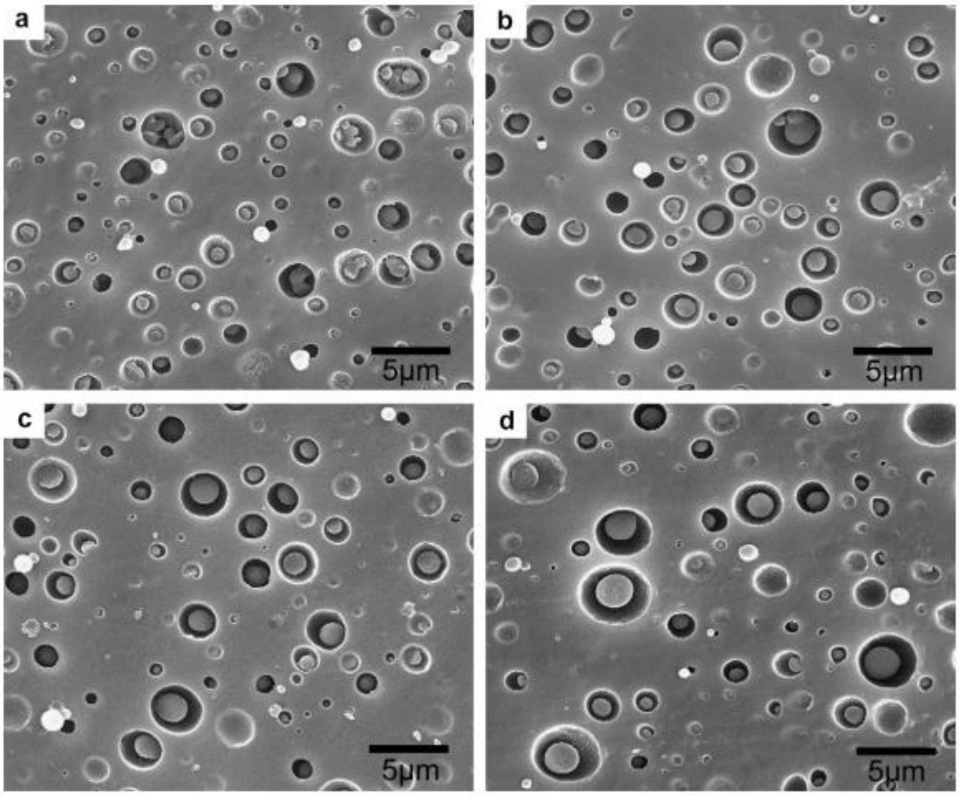


Figure 2.15: Scanning electron micrographs of HIPP after maintaining at 200℃ for a series of time (a) 10 minutes, (b) 30 minutes, (c) 100 minutes and (d) 200 minutes (Chen, et al., 2007)

2.3.3.2 The Effects of Thermal Aging on Crystallinity of Isotactic Polypropylene

Generally, the physical properties of polymers will be based on the degree of crystallinity and the direction distribution of the crystalline amount fraction. Both factors normally alter when polymer is exposed to thermal aging. Jia and Raabe, (2006), have done a research to determine the effect of thermal aging on the crystallinity of isotactic polypropylene (iPP). The samples were put in the ovens and aged at temperature 90 ℃ and 120℃. Now, by using X-Ray Diffraction analysis the changes in degree of crystallinity of iPP at different aged temperature were observed.

From Figure 2.16, it was revealed that the crystalline amount fractions of both iPP samples aged at 90℃ and 120℃ have increases from an initial value of 45.8 vol% to 49.6 vol% and 65.6 vol% after 10 minutes thermal treatment. In other words, the crystallinity of both iPP samples increase during the first 10 minutes. For thermal treatment beyond 10 minutes, the crystalline volume fractions of iPP aged at 120℃ remain nearly stable whereas for iPP aged at 90℃ there is slightly increase further. Thus, the degree of crystallininity for iPP aged at 120℃ has reaches a constant level. Besides, the results also showed that at the beginning of thermal aging the rate of activation recrystallization of decrystallized material was high.

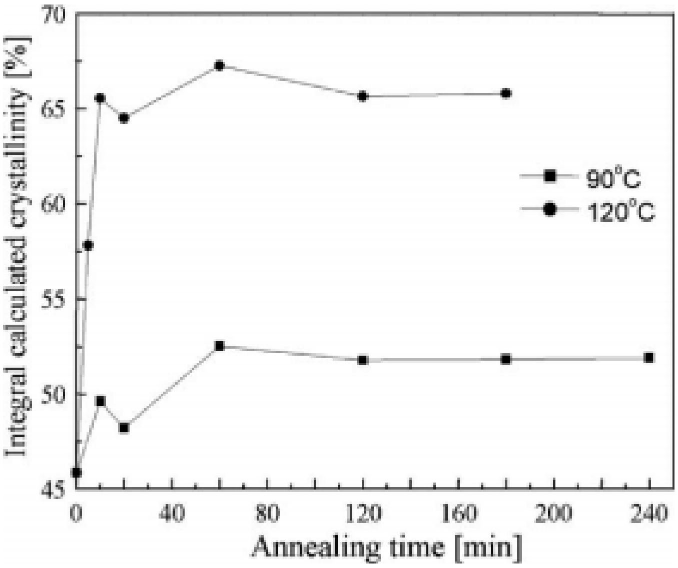


Figure 2.16: Effects of thermal aging time at two different temperatures on the crystallinity of isotactic polypropylene (Jia and Raabe, 2006).

2.3.3.3 The Effects of Thermal Aging on Crystallinity of Carbon Black/Polypropylene Blends

In another case, Horrocks, et al., (1999), have done a research on the thermal oven aging effect on carbon black properties of polypropylene (PP). Seven sets of samples were prepared with difference carbon black (CB) at concentration 2.5% w/w blended with PP. They were subjected to thermal exposure in an air oven at 130℃ for 20 days to promote sufficient oxidative degradation. The following Figure 2.17 showed the derived crystallinity of pure PP and CB/PP blends when oven-aging at 130 ℃. The crystalline structure of the polymer is usually observed in the results of an X-Ray Diffraction (XRD) test where the peaks represent the compound or bonds present in the polymer after thermal aging.

From the figure, it was observed that initially the crysallinity for all samples were increases with oven aging days and up to certain days the samples crystallinity begin to drop. Besides, samples of PP with carbon black have a lower crystallinity than pure PP at any oven aging time. The reason is because the degree of crystalline order of PP molecular chains was not improved by the presence of carbon black during oven aging. In this case carbon black did not have any effect on the crystallinity of the PP. Thus, it was concluded that the crystallinity of PP is generally affect by the oven aging. Initially the crystallinity of samples was observed to increase is because the thermal effect of the DSC technique itself. The increases of the crystallinity of samples are due to the formation of low melting temperature crystals. However, the crystalinity of samples decrease after thermally exposed for a certain duration and the reason is because chain scissioning reaction occurs. This network causes the molecular structure of samples unable to crystallize into orderly manner. In addition, the chain order was also disturbed by the presence of oxygenated groups and causing a decrease of the samples crystallinity (Guisandez, et al., 2005).

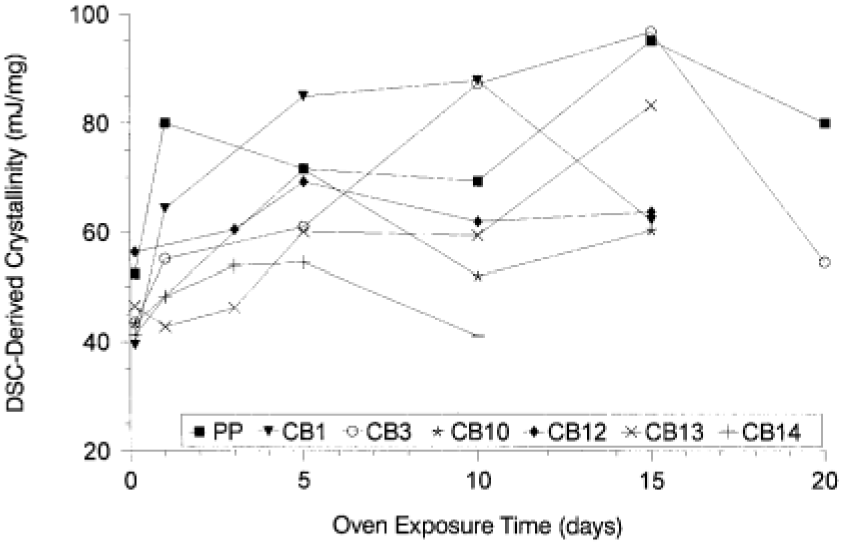


Figure 2.17: Effect of oven aging at 130℃ on DSC- derived crystallinity for PP containing various carbon blacks at 2.5% w/w concentration (Horrocks, et al., 1999)

CHAPTER 3

METHODOLOGY

3.1 Materials

In the following section, all the materials that needed in the study of irradiated PS are shown. The materials included is pure polystyrene (PS) and the specifications of polystyrene were described in the section below.

3.2 Polystyrene

The polystyrene used was Tairirex GPPS-5350 grade which was made in Taiwan. The melt flow index of this material is 4.5g/10 min and the density is 1040 kg/m^3.

3.3 Formulation

Table 3.1: Formulation of Electron Beam Electron Irradiation Dosage on Polystyrene and Aging under Oven Treatment with different Temperature

Condition	Sample	Electron beam Irradiation Dosage (kGY)	Temperature under Oven Treatment (℃)
Control(CT)	PS-0-CT	0	-
	PS-50-CT	50	-
	PS-100-CT	100	-
	PS-150-CT	150	-
	PS-200-CT	200	-
	PS-250-CT	250	-
Constant(CS)	PS-0-80-CS	0	80
	PS-0-100-CS	0	100
	PS-50-80-CS	50	80
	PS-50-100-CS	50	100
	PS-100-80-CS	100	80
	PS-100-100-CS	100	100
	PS-150-80-CS	150	80
	PS-150-100-CS	150	100
	PS-200-80-CS	200	80
	PS-200-100-CS	200	100
	PS-250-80-CS	250	80
	PS-250-100-CS	250	100
Ramp(RP)	PS-0-80-RP	0	80
	PS-0-100-RP	0	100
	PS-50-80-RP	50	80
	PS-50-100-RP	50	100
	PS-100-80-RP	100	80
	PS-100-100-RP	100	100
	PS-150-80-RP	150	80
	PS-150-100-RP	150	100
	PS-200-80-RP	200	80
	PS-200-100-RP	200	100
	PS-250-80-RP	250	80
	PS-250-100-RP	250	100

3.4 Sample Preparation

In this study, the samples were prepared by using this equipment: hot press machine, pneumatic tensile cutter, electron beam irradiation machine and oven. First, the powder form polystyrene was compressed into 1 mm × 15 cm × 15 cm sheets by using Lotus Scientific L5-11009 hot presser. Then, the samples were continued to place in the hot press machine with under pressure for 5 minutes. After that, the samples were took out and placed in front of a standing fan to let the sample cool down. Thereafter, the sample was cut into dumbbell shape that was based on ASTM D1822 standard by using Cometech QC-603A pneumatic tensile cutter. The cut samples were subjected to electron beam radiation at room temperature to the irradiation dosages of 50 kGy, 100 kGy, 150 kGy, 200kGy and 250 kGy. The irradiated samples were then subjected to constant thermal aging (at 80℃ and 100 ℃) and ramp temperature aging (from 30℃ to 80℃ and from 30℃ to 100 ℃) in Memmert Universal Oven for 2, 4, 6 and 8 days. The temperature profiles of the aging method are shown in Figure 3.1, Figure 3.2, Figure 3.3 and Figure 3.4.

3.5 Aging Operation

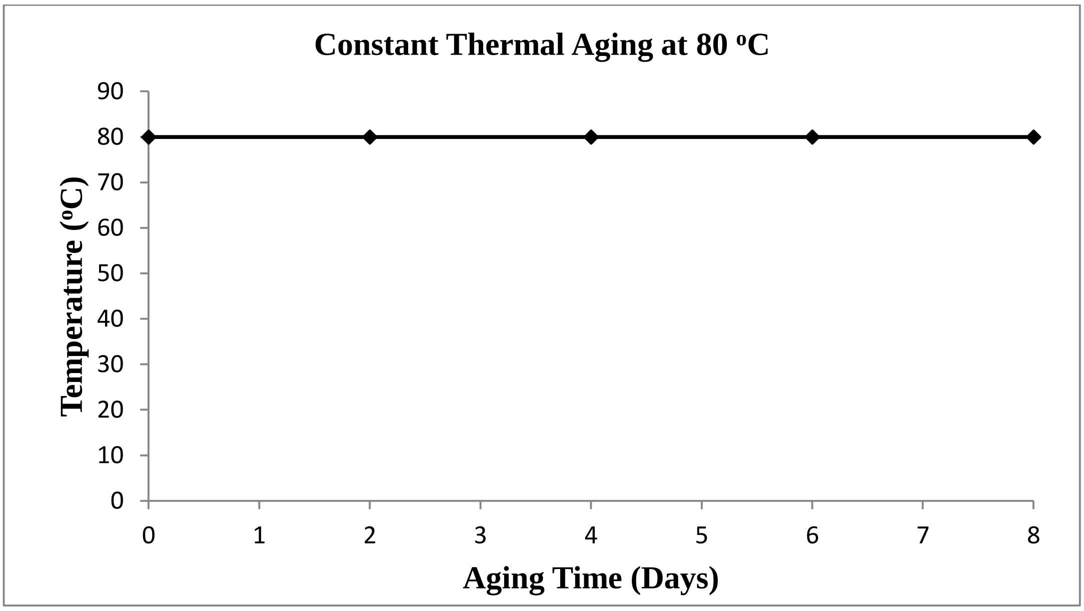


Figure 3.1: Constant Thermal Aging at 80℃

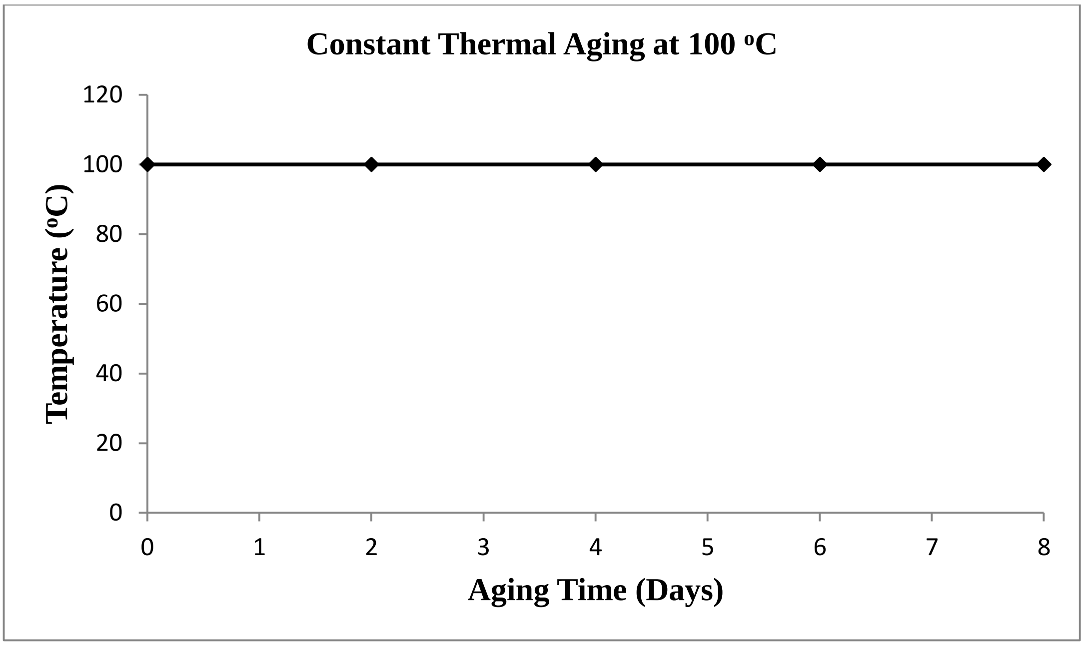


Figure 3.2: Constant Thermal Aging at 100℃

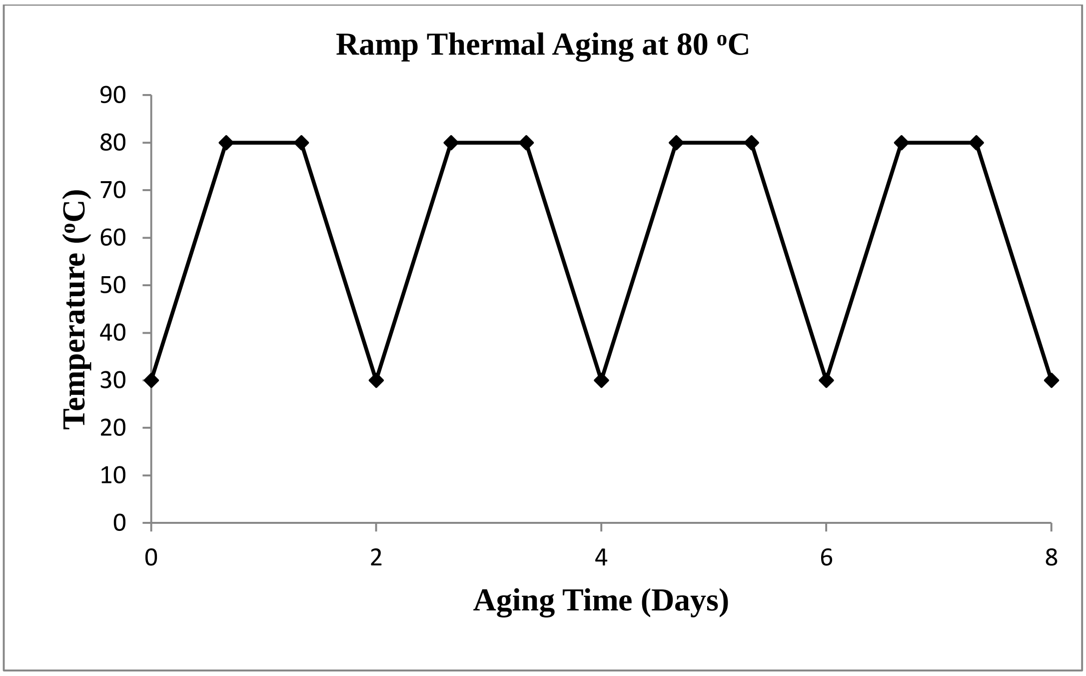


Figure 3.3: Ramp Thermal Aging at 80℃

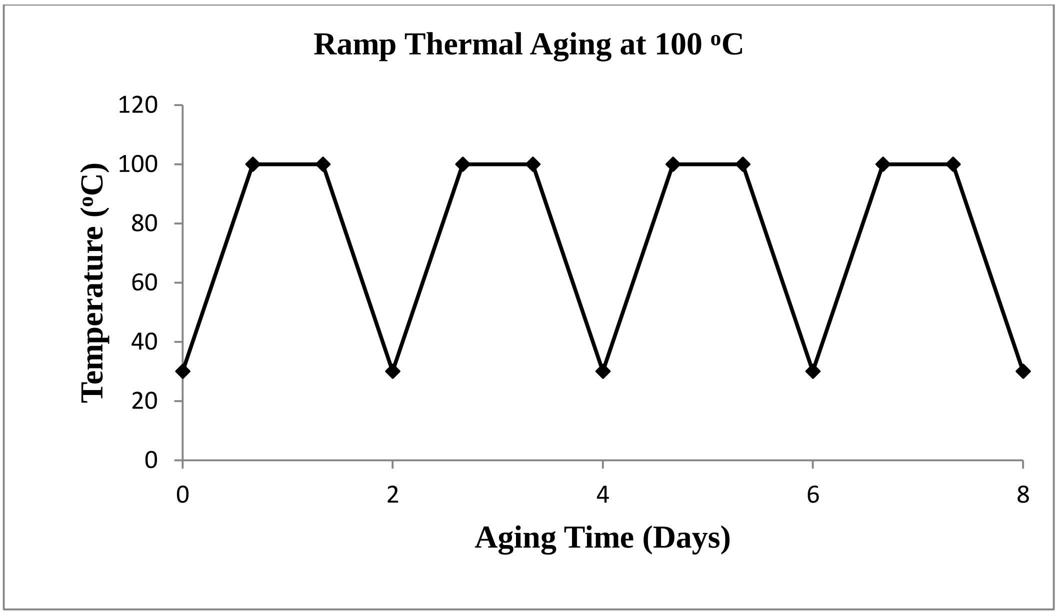


Figure 3.4: Ramp Thermal Aging at 100℃

3.6 Sample Testing

After the samples were prepared, they will be characterized through the following testing procedures.

3.6.1 Tensile Test

The mechanical properties of the sample according to the ASTM D1822 standard were evaluated by tensile test, using Instron Universal Testing Machine 5582 series IX tensile tester. The measurement was carried out at room condition, 25°C, with constant load cell of 2 kN and crosshead speed of 50 mm/min. Three tensile parameters, namely tensile strength, elongation at break and Young's modulus of each sample were obtained directly from the tensile datasheet with the aid of Bluehill software.

3.6.2 Differential Scanning Calorimetry (DSC) Analysis

In order to characterize the melting behaviours of the samples, the samples were subjected to Differential Scanning Calorimetry (DSC) analysis by using Mettler-Toledo DSC823E/200 analyzer. In each measurement, 5 – 8 mg of sample was heated dynamically from 30 to 200 ℃ at constant heating rate of 10 ℃/min. Dry nitrogen gas at constant purge rate of 20 mL/min was applied for purging purpose throughout the entire measurement. Both melting temperature (T_m) and melting heat (ΔH_m) of each analyzed sample were obtained directly from the DSC thermogram that was generated by Star^e software.

3.6.3 Scanning Electron Microscopy (SEM) Analysis

The morphologies of fractured surface of samples from tensile test were observed by using JOEL JSM-3301F Scanning Electron Microscopy. After the completion of tensile test, the fractured region of the sample was cut and placed onto a copper stub such that the fractured surface facing directly to the electron gun. All the samples were scanned under magnification of ×3000, ×5000 and ×8000.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Mechanical Properties Analysis

4.1.1 Tensile Strength

The tensile tests were performed on pure irradiated PS without aging, aged irradiated PS at both constant 80℃ and 100℃ and both ramp 80℃ and 100℃. The results of the tensile strength of PS following to a range of irradiated PS and aging temperature were illustrated in Figure 4.1, 4.2, 4.3 and 4.4. These results were displayed with respect to the irradiated and non accelerated aged irradiated PS which acted as a reference. The PS samples were irradiated at low irradiation dosages range from 50kGy to 150kGy and high irradiation dosages range from 200kGy to 250kGy. Figure 4.1 presented the tensile strength as a function of irradiation dosages aged at constant 80℃. The figure showed that for pure irradiated PS without aged, apart from high dosages irradiated PS, 200kGy and 250kGy samples, the tensile strength improved with an increased of irradiation dosages. The reason was because at integral low irradiation dose from 50kGy to 150kGy formation of crosslinking networks began. Oka, et al., 2003, mentioned that tensile strength has a close relationship to the crosslinking networks and the formation of crosslinking can guide to an improved in tensile strength. Crosslinking network will be formed by an increase in fusion of molecules and inter-crystal bonding (Al-Ali, et al., 2003). However, irradiated PS samples at 200kGy and 250kGy tensile strength dropped significantly. The significant decrease of tensile strength was due to serious chain scissioning reaction occurred in PS (Albano, et.al, 2003). The free radicals formed from the irradiation process are capable to react with oxygen to cause chain scissioning or react internally to form crosslinking networks (Premnath, et al, 1996). Furthermore, the decreased in tensile strength was also connected to the chemical reactions that are driven by the distinction in Gibbs free energy between the PS and reactants at certain conditions. The electron beam resulted in an increased in temperature of PS where an increase of 10℃ doubles the rate of reaction (Berejka and Cleland, 2011). An electrochemical effect happened between electrons and constituent atoms in PS when PS was irradiated with 200kGy and 250kGy.

From Figure 4.1, it was found that the tensile strength of aged irradiated PS at low irradiation dosages and high irradiation dosages decreased with aging days, comparing to pure irradiated PS without aging. The reason was because thermal degradation occurred. Thermal degradation refers to chemical and physical processes that happened at high temperature in polymers. Oxidation was generally considered to occur in PS when using at high temperatures. The relationship between oxidation process and temperature were highly depended on the chemical structure of PS. Thermo-oxidative was kicked off by the reactions of free radicals in PS with oxygen to form peroxide radicals. The free radicals contained in PS were due to hot pressed history. The formed radicals underwent slower propagation reactions which breakdown the polymer chain. Thus, it was observed the tensile strength of irradiated PS decreased slightly with increased aging time. (Maxwell, et al., 2005)

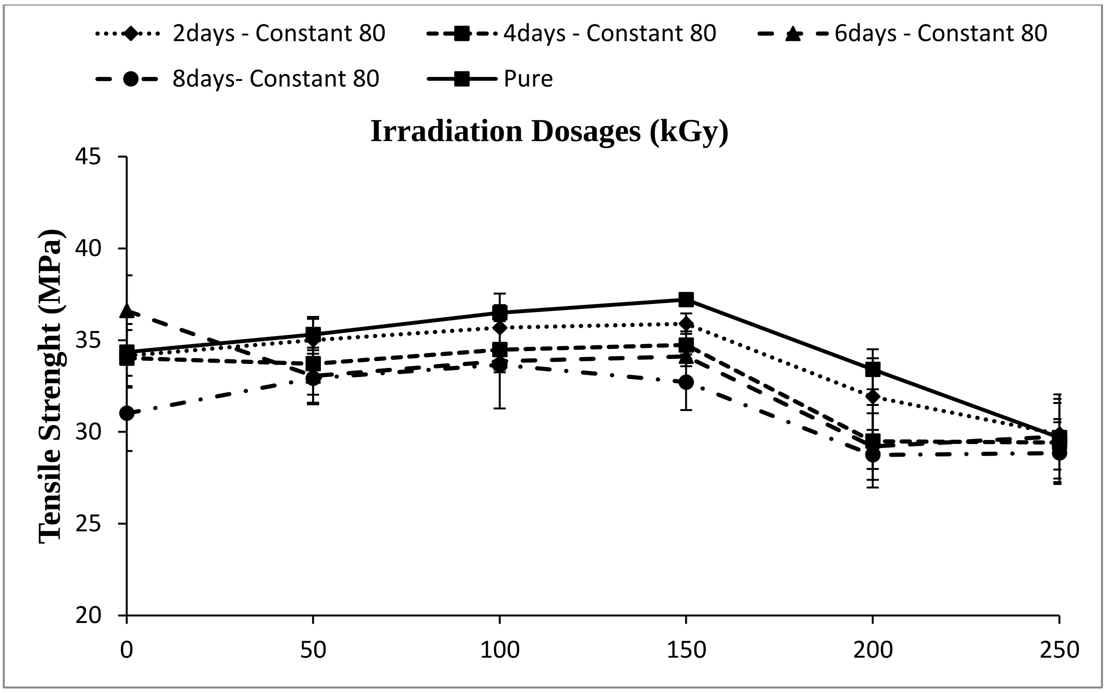


Figure 4.1: Tensile Strength against Irradiation Dosages at Constant 80℃ Aging

Figure 4.2 presented the tensile strength as a function of irradiation dosages aged at ramp 80℃. The figure showed that aged irradiated PS, apart from 200kGy and 250kGy, the tensile strength increased with aging time at integral irradiation dose from 50kGy to 150kGy. The reason was because thermal cycles increased inter-chain interaction in PS that attributed to an increase in crosslinking network density in PS (Bal, et al., 2007). Besides, molecular arrangement happened during ramp aging facilitated by slow heating rate for 16 hours, followed by constant heating and then slow cooling rate for 16 hours. This improved the chain packing inside PS which led to a change of the crystalline structure from the γ- to the ∝-phase (Kiliaris, et al., 2009). It is well well-known that the ∝-phase has higher melting point than γ-phase. The ∝-phase is thermodynamically more stable and preferentially structured in conditions involving high crystallization temperatures or low cooling rates (Pavlov, et al., 1989).

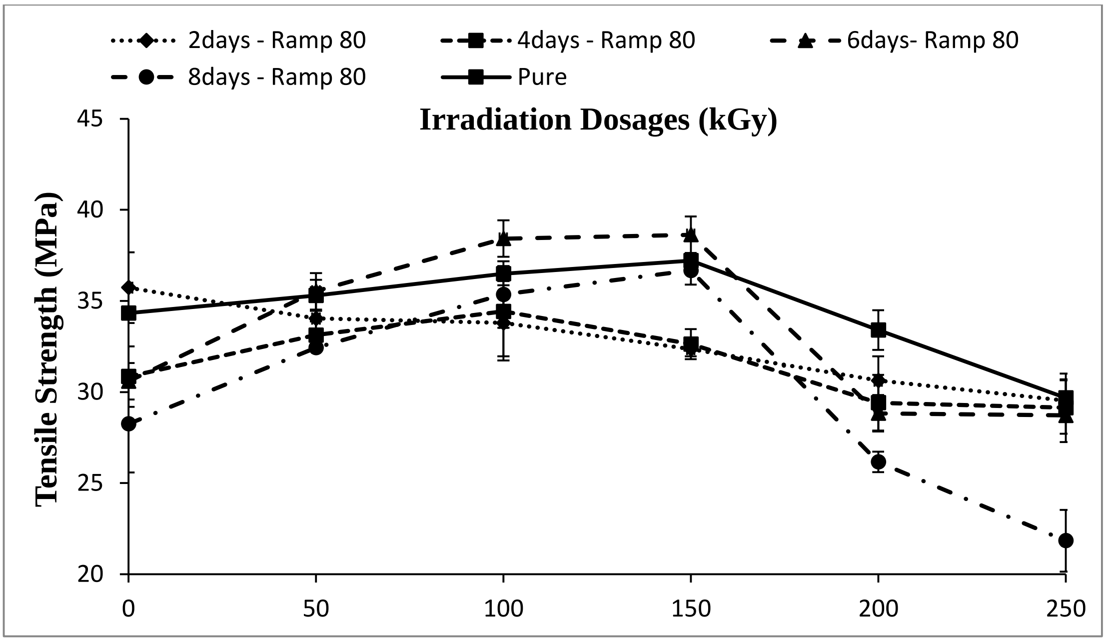


Figure 4.2: Tensile Strength against Irradiation Dosages at Ramp 80℃ Aging

Figure 4.3 presented the tensile strength as a function of irradiation dosages aged at constant 100℃. The figure showed aged temperature above T_g of PS has high effect on crosslinking density. Apart from 50kGy to 150kGy irradiated PS aged 6 days, the tensile strength decreased with irradiation dosages at integral irradiation dose from 50kGy to 150kGy. The reason was because at aging temperature above T_g of PS, breaking of crosslinking network. However, 50kGy to 150kGy irradiated PS aged 6 days, the tensile strength increased. The reason was because the free radicals formed due to crosslinking chain breaking caused by high temperature started to react with oxygen after prolonged aging in oven at temperature above T_g caused PS structure further chain scissioned. This lowered the molecular weight of PS as discussed by Premnath, et al., 1996. Therefore, the freedom of movement of the chain improved whereby some of the entangled, amorphous PS chains are able to reorganize themselves into a lower energy state of crystalline (Buchanan, et al. 2001). In other words, the PS structure re-crosslinked caused the tensile strength increased but it could be observed that the tensile strength of re-crosslinked PS samples unable to restore to the original tensile strength. Thus, it could be observed the tensile strength of re-croslinked PS samples were lower than pure PS without aging. Moreover, further aged of irradiated PS, 8days, the tensile strength dropped significantly at integral irradiation dose from 50kGy to 200kGy.

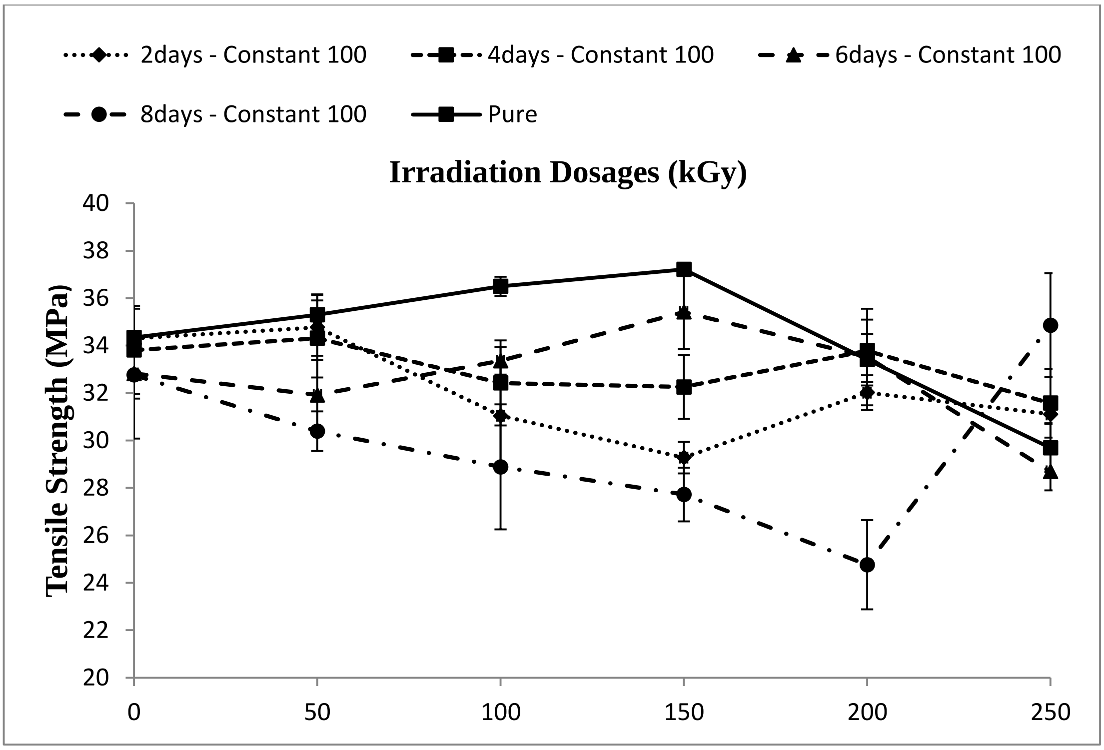


Figure 4.3: Tensile Strength against Irradiation Dosages at Constant 100℃ Aging

Figure 4.4 presented the tensile strength as a function of irradiation dosages aged at ramp 100°C. It could be observed that tensile strength for irradiated PS ramp aged at 100°C has a similar trend compared to Figure 4.1. The reason was because ramp aging at 100°C did not provide as harsh as constant 100°C.During ramp aging the irradiated samples the inter-chain interaction of PS increased attributed to increased of crosslinking density. In addition, the figure also showed that increased the exposure time under ramp aging tends to increased tensile strength and then prolonged heating the tensile strength decreased.

Apart from that, 250kGy irradiated PS showed a sharp increased in tensile strength at the 8th day of aging. The reason was because prolonged heating causes thermal degradation and form low molecular weight chains. As the chains continued breaking, shorter chains was formed. This enabled the shorter chains to recrystallization easily compared to long chains during slow cooling rate (Mandelkern, 1964). As results, the tensile strength skyrocketed.

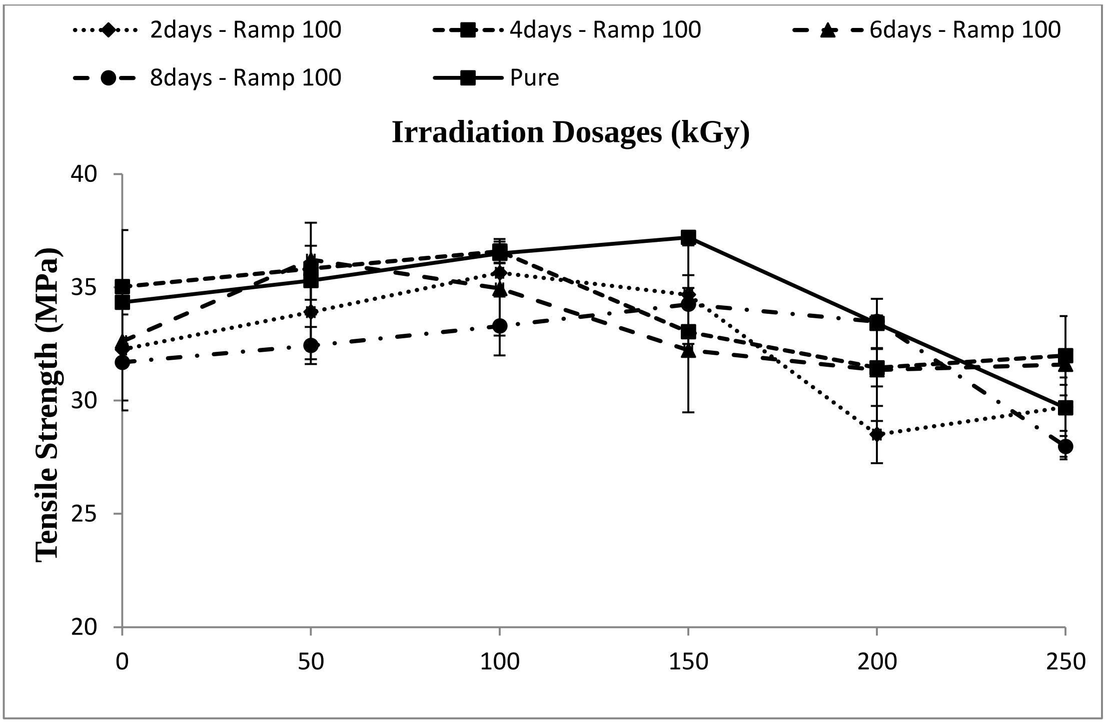


Figure 4.4: Tensile Strength against Irradiation Dosages at Ramp 100℃ Aging

4.1.2 Percentage Elongation at Break

Elongation at break is also known as fracture strain which expresses the ability of a material to oppose changes of shape with no crack formation. A brittle polymer generally has a shorter elongation at break. PS in nature is a brittle material in which, it break right after reached it ultimate tensile strength.The results of the percentage elongation at break of PS following to a range of irradiated PS and aging temperature were illustrated in Figure 4.5, 4.6 , 4.7 and 4.8. These results were displayed with respect to the irradiated and non accelerated aged irradiated PS which acted as a reference. Figure 4.5 presented the percentage elongation at break as a function of irradiation dosages aged at constant 80℃. The figure showed that, apart from 200kGy and 250kGy samples, the percentage elongation at break decreased with an increased of irradiation dosages. Elongation at break was sensitive to the increased in irradiation dosages. The decreased of percentage elongation at break indicated an increased in brittle tensile behaviour of PS. The reason was because crosslinking reduced the strain deformation ability of PS which in turn restrained the ultimate chain stretch. However, irradiated PS samples at 200kGy and 250kGy the percentage elongation at break increased significantly. This indicated that the chain scissioning process happened and more main than crosslinking process at high irradiation dosages. The reason was because the high energy of electron beam causes chain scission of PS by breaking the bonds between the molecules in the main chain of PS.

From Figure 4.5, the percentage elongation at break of aged irradiated PS increased with aging days, comparing to pure irradiated PS without aging. The reason was because thermal degradation occurred. Thermo-oxidative degradation generally changes the PS crystallinity. As the aging time increased, the crystalline content gradually decreased which caused by thermo-oxidative degradation. Moreover, the aged irradiated PS slowly underwent transition from brittle behaviour to mere elastic behaviour. This was due to decreased in crystalline content and constant heating caused crosslinking chain over stretched and began to break slowly.

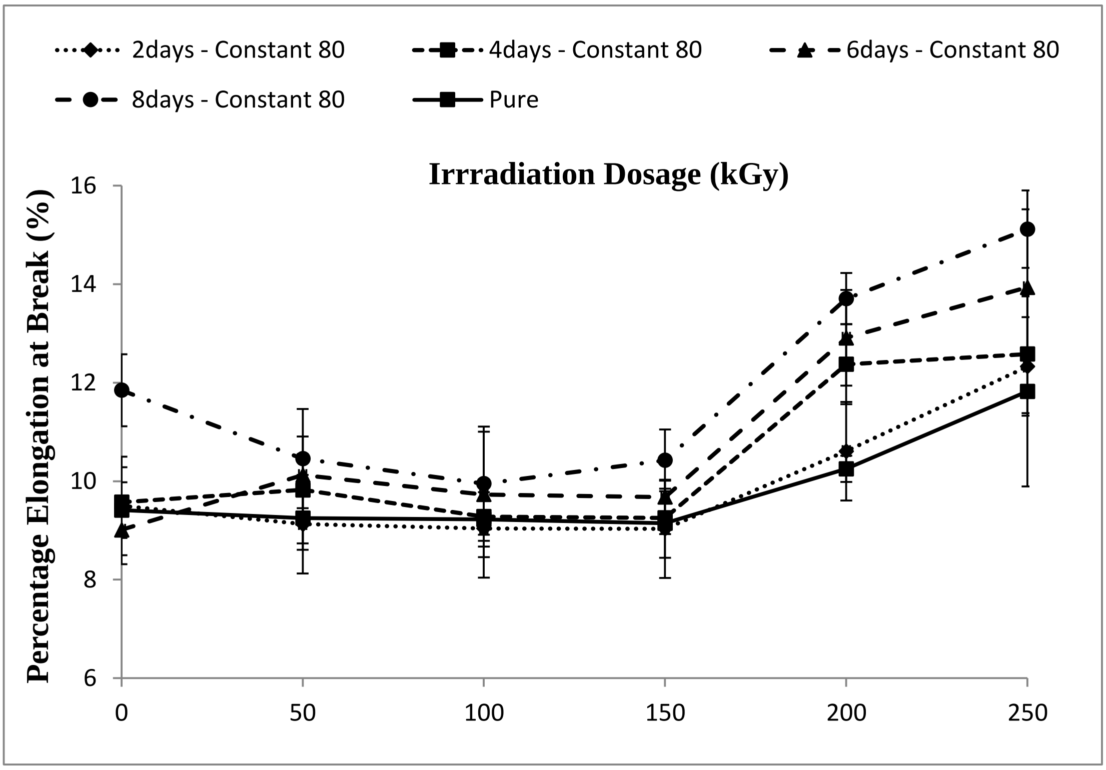


Figure 4.5: Percentage Elongation at Break against Irradiation Dosages at Constant 80℃ Aging

Figure 4.6 presented the percentage elongation at break as a function of irradiation dosages aged at ramp 80℃. The figure showed the similar trend as compared to Figure 4.5. It could be observed that apart from 200kGy and 250kGy samples, the percentage elongation at break decreased with an increased of irradiation dosages. Comparing with Figure 4.5, the percentage elongation at break for irradiated PS aged at constant 80℃ were higher than irradiated PS aged at ramp 80℃. This might due to the slow cooling rate of ramp aging caused a small amount of the scission chain re-crosslinked. Besides, heating and holding of PS at a suitable temperature below the crystalline melting point will create a slight increase in crystalline structure in PS as well as relieving stress (Peterson, et al., 2011).

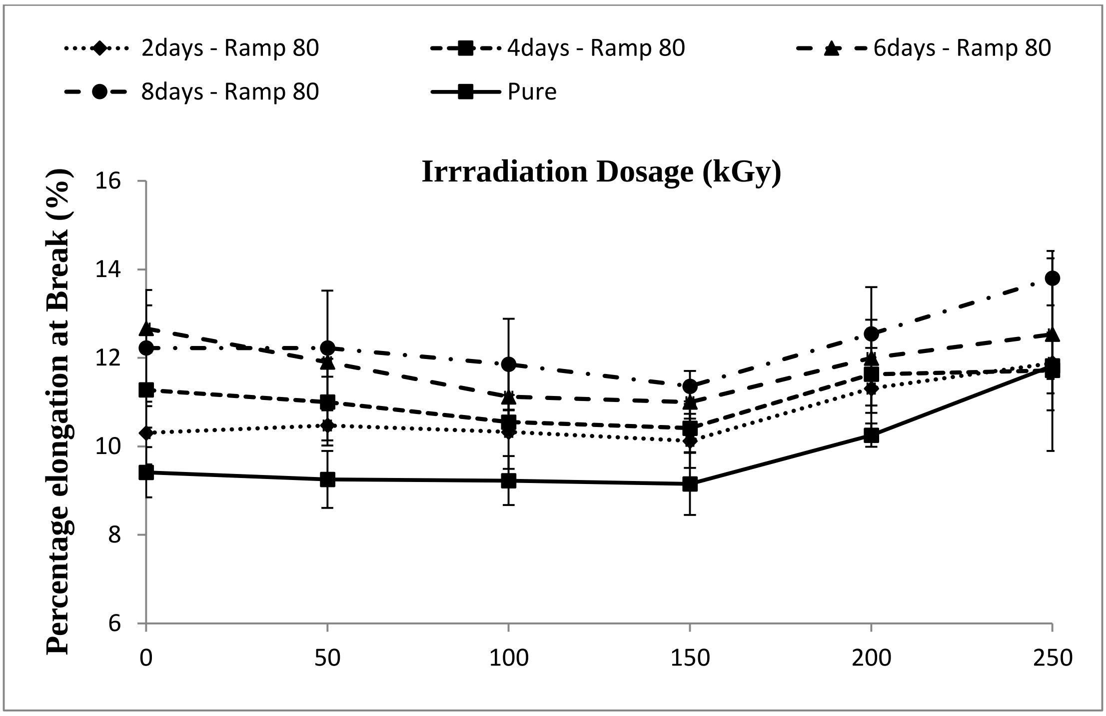


Figure 4.6: Percentage Elongation at Break against Irradiation Dosages at Ramp 80℃ Aging

Figure 4.7 presented the percentage elongation at break as a function of irradiation dosages aged at constant 100℃. It could be observed that percentage elongation at break increased significantly compared to Figure 4.5 and 4.6 where the irradiated PS aged at both constant and ramp 80℃. The significant increased in percentage elongation at break was due to the effects of chain scissioning dominant process which produced shorter polymer chains. This enhanced the mobility n the polymer matrix, reduced the stiffness of PS. Besides, the figure showed the percentage elongation at break for aged 100℃ of irradiated PS at 200kGy, dropped significantly. At 200kGy, the short chains produced during electron irradiation were further chain scissioned. These shorter chains were able to rearrange themselves into lower state of crystalline energy which restricted the movement in matrix and reduced the extendability of PS. Thus, affected then tensile strength of PS and became more brittle.

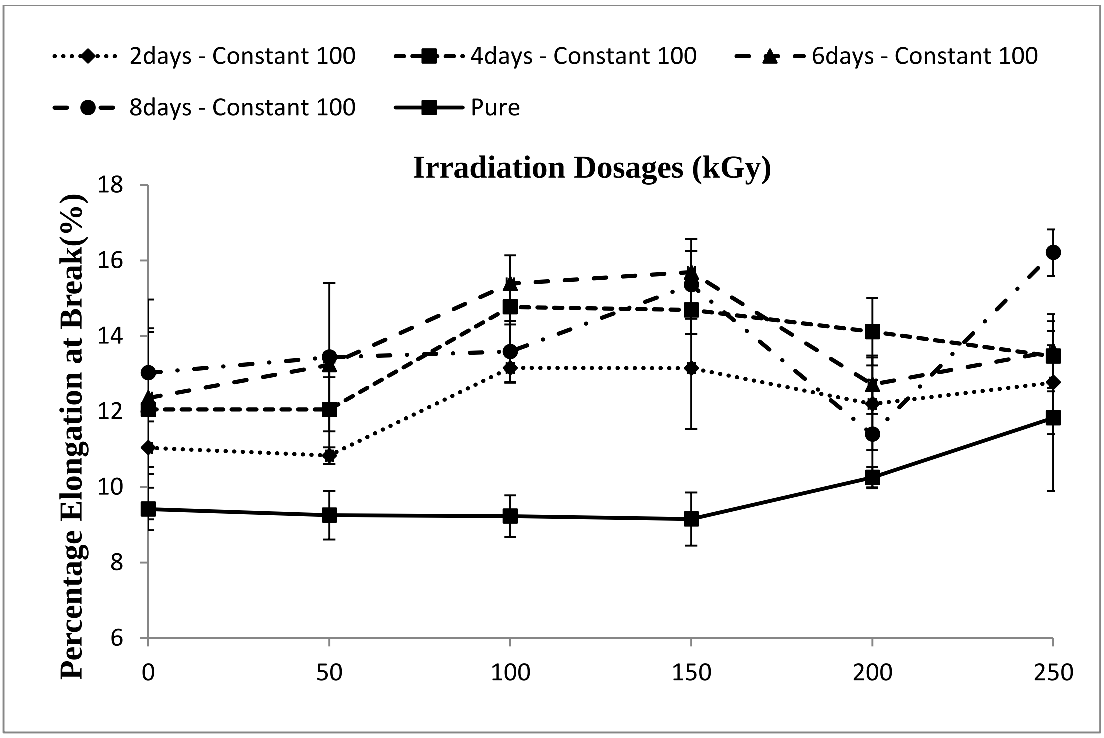


Figure 4.7: Percentage Elongation at Break against Irradiation Dosages at Constant 100℃ Aging

Figure 4.8 presented the percentage elongation at break as a function of irradiation dosages aged at ramp 100℃. From the figure, apart from 200kGy and 250kGy irradiated PS, it showed the percentage elongation at break decreased with increased in irradiation dosages. This was due to the cooling effect from slow cooling rate when aged under ramp conditions. The slow cooling rate enables the polymers chain to reorganize into tightly packed structure. Thus, the crystallinity of PS increased and the addition effect from crosslinking network produced during low dosages of electron beam irradiation generally reduced the percentage of elongation at break. On the other hands, the percentage elongation at break of PS irradiated at high dosages does not reduced when aged under ramp conditions. Comparing to Figure 4.7, the irradiated PS showed a reduction in percentage of elongation at break due to the harsh aging condition caused more shorted chain to produce which able to cause recrystallization. In addition, the pendant group of irradiated PS opened due to elevated temperature aging which enhanced the movement in the polymer matrix. In ramp conditions, however, the short chain produced during high irradiation dosage did not underwent further chain scissioning leaving the chain in medium size. This medium size chains unable to reorganize themselves due to the pendant group ring of PS restricted the mobility in the structure. Moreover, the percentage elongation at break of irradiated PS aged at constant 80℃ were lower comparing to irradiated PS aged at ramp 80℃ and both constant and ramp 100℃. This indicated that not only aged above the T_g PS of will induce an elastic behaviour in PS; ramp aging also caused the PS to become slighty soft and elastic. (Bal, et al., 2007)

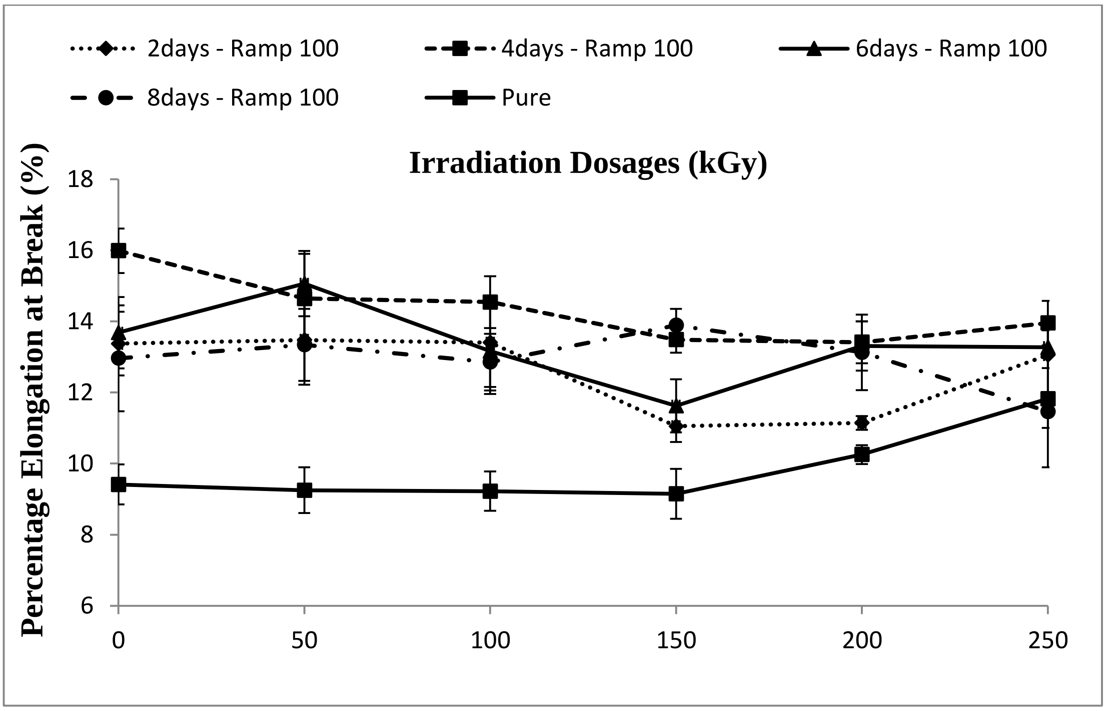


Figure 4.8: Percentage Elongation at Break against Irradiation Dosages at Ramp 100℃ Aging

4.1.3 Young’s Modulus

Young’s modulus is a measure of the stiffness of an elastic material and also known as tensile modulus. The results of the tensile modulus of PS following to a range of irradiated PS and aging temperature were illustrated in Figure 4.9, 4.10, 4.11 and 4.12. Figure 4.9 presented the tensile modulus as a function of irradiation dosages aged at constant 80°C. From Figure 4.9, it showed the trend of young modulus was similar to that of tensile strength. This corresponds with the research done by Goulas, et al., 2004. It From Figure 4.9 , it could be observed that apart from 200kGy and 250kGY irradiated PS samples, the tensile modulus increased with irradiation dosages which tally with tensile strength results. The reason was because irradiation at low dosages causes the formation of crosslinking between PS chains that perhaps intensity the stiffness. In other words, the crosslinking network resisted the pulling force and which improved the tensile modulus and tensile strength. However, irradiated PS samples at 200kGy and 250kGy tensile modulus dropped significantly. The significant decrease of tensile modulus was due to serious chain scissioning reaction occurred in PS (Murray, et al., 2013).

Apart from that, it was found that tensile modulus of irradiated PS samples decreases with an increase in aging times. The reason was because constantly heating on irradiated PS samples cause thermal degradation. Thus, the chains of PS slowly break and the prolonged heating caused the opening of PS pendant group ring which reduces the inter-molecular chain and inflexibility. (Peterson, et al., 2011)

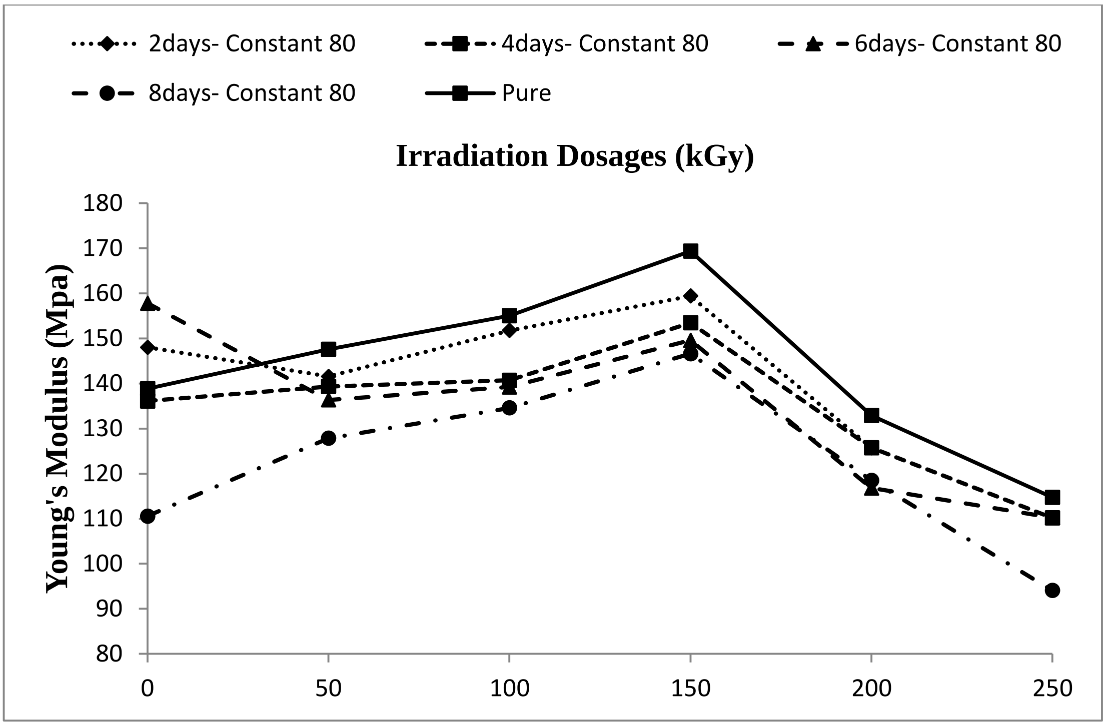


Figure 4.9: Young's Modulus against Irradiation Dosages at Constant 80℃ Aging

Figure 4.10 presented the tensile modulus as a function of irradiation dosages aged at ramp 80℃. Comparing Figure 4.9 and 4.10, both showed the similar trends where crosslinking increased the tensile modulus whereas chain scissioning decreased the tensile modulus. Besides, tensile modulus also decreased with aging time caused by thermal degradation. However, it could be seen clearly the tensile modulus of irradiated PS samples aged at ramp 80℃ have higher tensile modulus compared to irradiated PS aged at constant 80℃. The reason was because thermal cycles tend to increase the crosslinking density of PS structure and improved the crystallinity structures due to slow cooling rate effect of ramp aging.

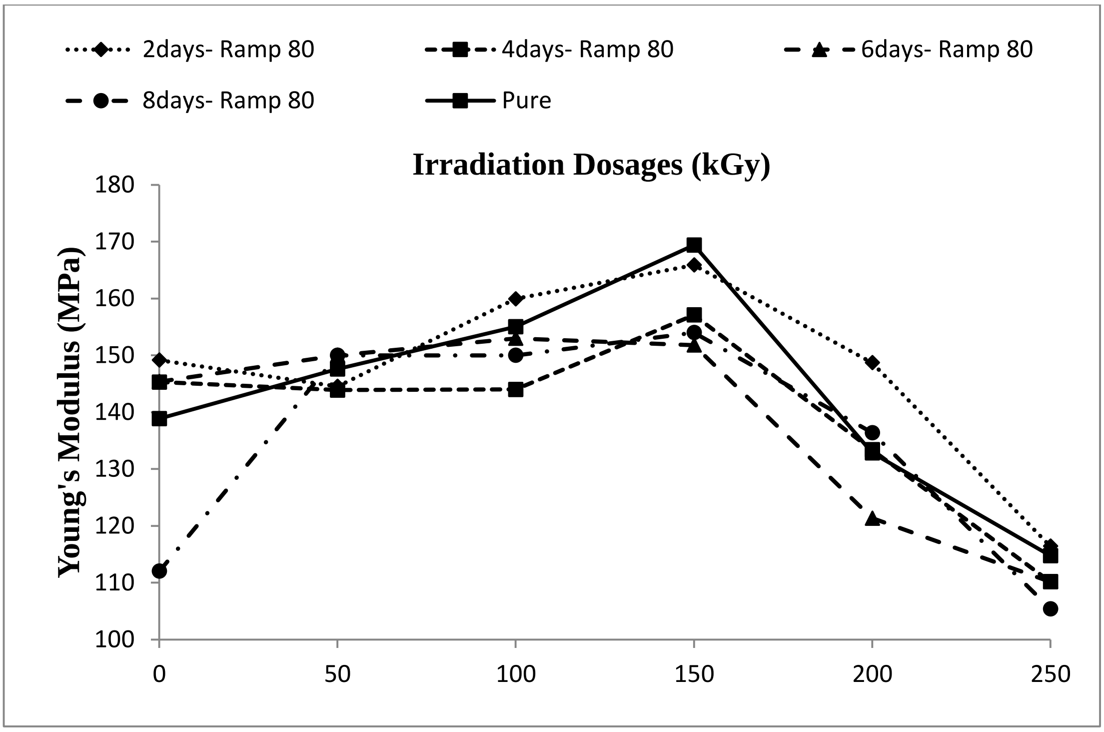


Figure 4.10: Young's Modulus against Irradiation Dosages at Ramp 80℃ Aging

Figure 4.11 presented the tensile modulus as a function of irradiation dosages aged at constant 100℃. Form the figure it could be seen that aged temperature above T_g of PS has high effect on crosslinking density which tally with tensile results. Apart from integral irradiation dose from 50kGy to 150ky for aged 6 days PS, the tensile modulus decreased with increased in irradiation dose. This is due to aging temperature above T_g of PS, breaking of crosslinking network which released free radicals that enhanced the thermal degradation processes where the free radicals react with oxygen. High density of crosslinking generally released more free radicals upon heating above the PS, T_g. Hence, it could be observed that the tensile modulus of 150kGy irradiated PS lower than other irradiation dosages. (Premnath, et al., 1996)

Nevertheless, 50kGy to 150kGy irradiated PS aged 6 days showed an increased in tensile modulus. This could be explained by the re-crosslinking effects. The prolonged heating cause shorter chains to produce which improved the movement of chains. The short chains able to reorganize themselves caused an increased in tensile modulus.

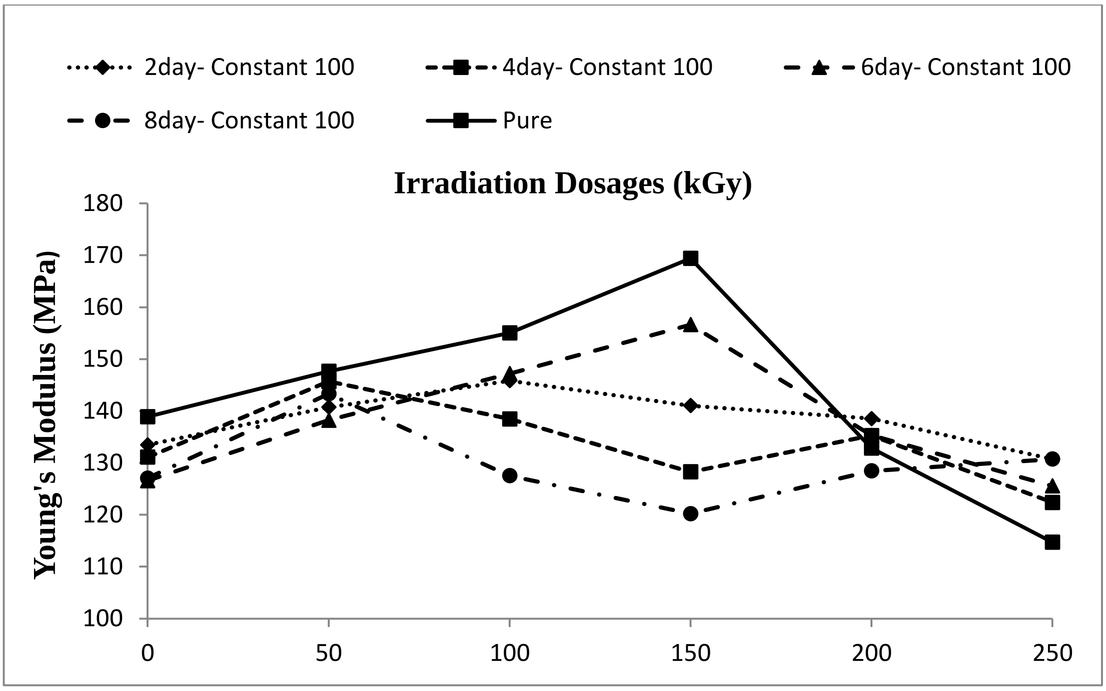


Figure 4.11: Young's Modulus against Irradiation Dosages at Constant 100℃ Aging

Figure 4.12 presented the tensile modulus as a function of irradiation dosages aged at ramp 100℃. Form the figure it could be seen that ramp aged of PS has less effect on young modulus compared to constant aged. The reason is because constant aged provide a harsher environment that ramp aged. Besides, during ramp aging the irradiated samples were cooled slowed which cause formation of crystalline structure even after heated above T_g of PS. However, the figure showed that PS irradiated with high irradiation dosages showed a slight increased in tensile modulus. Wang, et al., 1999, mentioned that the shorter chains are more readily able to organize themselves into crystalline state than longer molecules during cooling. Thus, during ramp aging the slow cooling rate allow shorter chains to re-crosslinking and enhanced the tensile modulus.

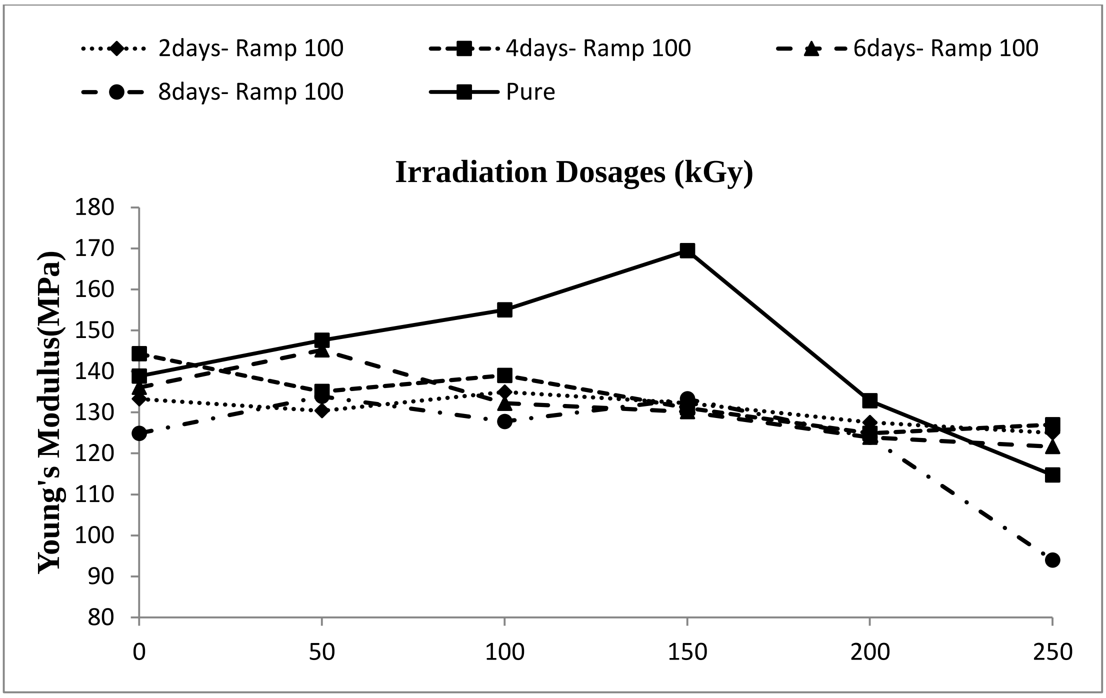


Figure 4.12: Young’s Modulus against Irradiation Dosages at Ramp 100℃ Aging

4.2 Thermal Properties Test

4.2.1 Differential Scanning Calorimetry (DSC) Analysis

The differential scanning calorimetric (DSC) were performed on pure PS without aging and irradiation, aged irradiated PS at constant 100℃ and ramp 100℃. The results of the differential scanning calorimetric thermograms of aged irradiated PS samples were illustrated in Figure 4.13, 4.14, 4.15 and 4.16. Figure 4.13, showed the results of DSC for irradiated PS without aging. In the thermogram, it could be noticed that there was presence of endothermic peak at the temperature of 90℃ to 120℃ which showed melting state. Peak area in the thermogram was very important for indicating whether the intermolecular bonding within the structures was strong or weak. The peak area could state the amount of thermal energy which was needed to transform into kinetic energy. Smaller peak area represents that the material only required a little amount of kinetic energy to enable the material molecules free out from the good crystalline structure. (Tee, et al., 2013)

From Figure 4.13, it could be seen that apart from pure irradiated PS at 200ky, the melting point increased at pure irradiated PS at 100kGy. The reason was because, the bonding spectrum of pure irradiated PS at 100kGy was narrower and shaper. This was generally due to crosslinking network produced during electron beam irradiation at low dosages. The crosslinking networks increased the crystallinity of PS and hence increased the melting temperature. On the other hands, pure irradiated PS at 200ky the bonding spectrum was slightly broader and less sharp. Thus, melting temperature reduced. This was due to chain scicionning effects. This caused low molecular weights chains produced which are generally weaker in strength. These chains are crystalline but only weak Van der Waals' forces grip the lattice together. Thus, reduced the melting temperature and lower than pure PS and pure irradiated PS at 100ky.

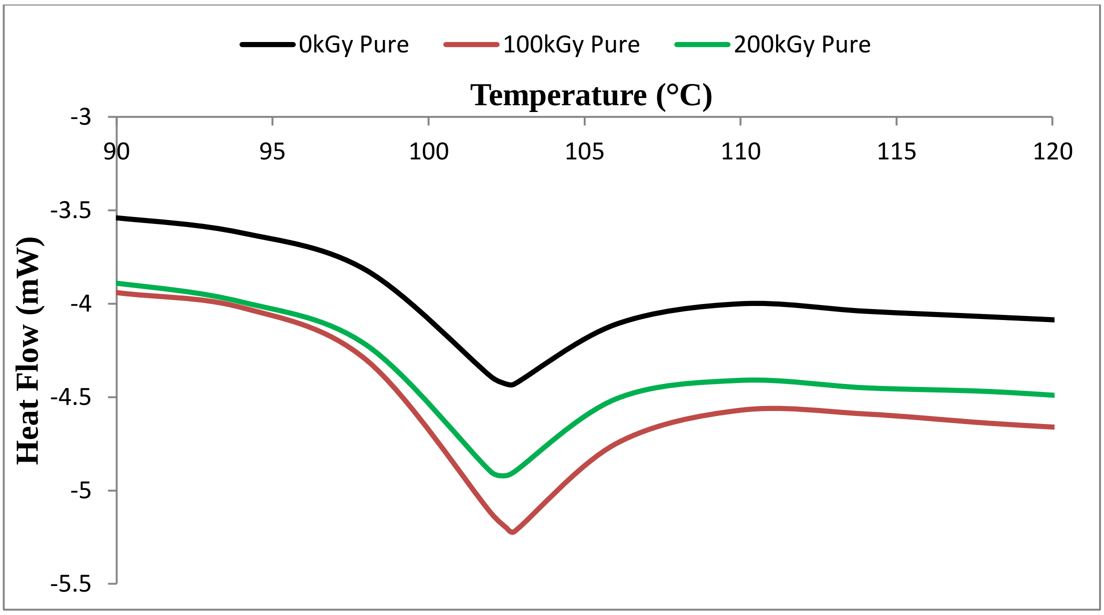


Figure 4.13: Differential Scanning Calorimetry (DSC) results of Pure Irradiated PS

Besides, from Figure 4.13, it could be observed that the bonding spectrum for pure irradiated PS without aging was narrower and shaper; whereas from Figure 4.14 the bonding spectrum of irradiated PS with aged at constant temperature conditions was much broader and round in shape. Thus, it could be observed that the melting temperature of pure irradiated PS without aged was higher than irradiated PS with aged at constant 100℃. The broader bonding spectrum indicated that the bonding was strong and coordinated. For this kind of bonding, the structure has high crystallinity. Thus, higher energy was needed to enable the molecules of polymer to free out from the structure for the structure which consisted of high crystalline structure. Comparing to irradiated PS aged for constant 100℃, showed that chain scissioning and thermal oxidative degradation has took placed after aged at elevated temperature above T_g of PS, which was proved by a declined in the melting temperature and the form of broader melting peak. In other words, the harsh thermal oxidation causes the growth of a robustly degraded crystalline part. Thus, the melting temperature decreased.

Apart from that, it was also found that the melting temperature changed with respect to thermal aging durations. It could be observed that the melting temperature of aged pure PS decreased with increased of aging time. The declination of melting point was due to thermal degradation occurred in the samples. However, comparing with irradiated PS at 100kGy, the melting point increased at integral aging time from 2 days to 6 days and then followed by a decreased in melting point at the 8th days of aging. The increased can be explained by a post-curing phenomenon that increased the cross-linking density (Merino, et al.2014). The irradiated PS at 100kGy aged for 8 days showed a considerable decrease in the melting point can be explained by a thermal-oxidative degradation phenomenon in the PS matrix. The melting temperature of aged irradiated PS at 200kGy showed the similar trends happened but the melting point was slightly higher than aged irradiated PS at 100kGy. This can be explained by chain scissioning effect from high irradiation dosages were underwent further chain breaking into a shorter and lower molecular weight. Thus, the structure re-crosslinked and formed a weak crystalline structure. The crystalline structure cause melting point increased slightly but remained lower than pure PS.

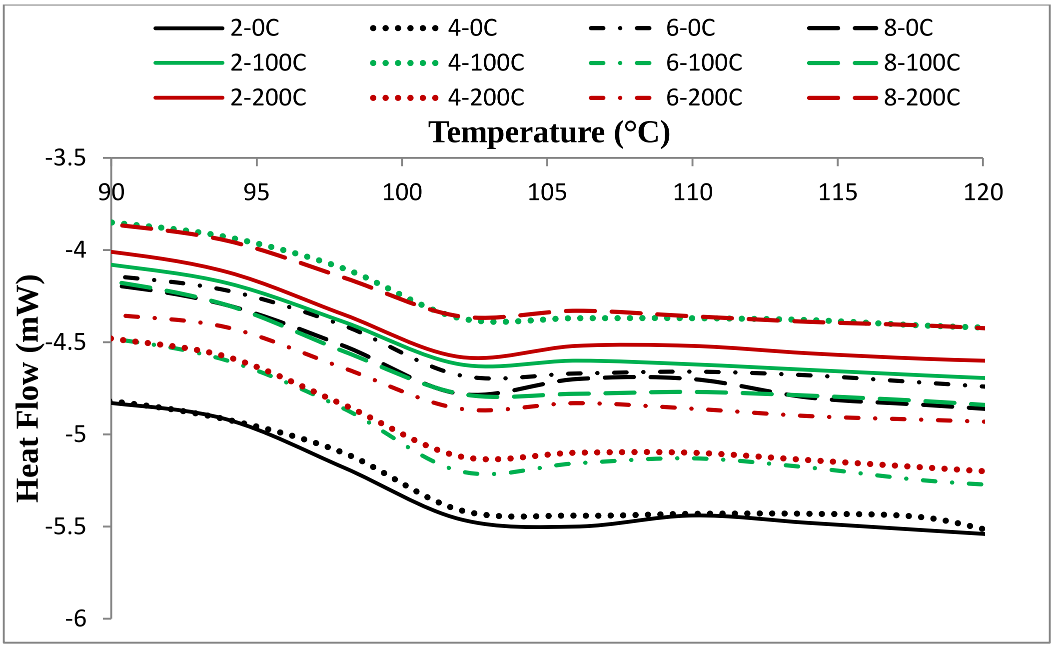


Figure 4.14: Differential Scanning Calorimetry (DSC) results of Irradiated PS Aged at Constant 100℃

Figure 4.15, showed the results of DSC for irradiated PS aged at ramp 100℃. Comparing Figure 4.15 with Figure 4.14 it could be observed that the bonding spectrum for irradiated PS heated at ramp 100℃ have narrower and sharp peak compare to aged irradiated PS at constant 100℃. This indicated constant aging condition cause irradiated PS to undergo thermo-oxidative degradation faster than ramp aging conditions. This was proved by the increased melting point of irradiated PS heated at ramp 100℃. The reason was because thermal ramp cycles tend to increase the inter-chain interaction that attributes to crosslinking network formation. Besides, ramp aging condition generally influenced the amount of crystallinity in PS. During ramp aging the irradiated PS underwent slow heating rate, followed by constant heating rate and then slow cooling rate. The slow cooling rate provided time for larger amounts of crystallization to occur. On the other hand, fast cooling rate yielded highly amorphous structure of PS. This caused the melting temperature to shift to a slightly higher temperature compare to irradiated PS samples aged at constant 100°C. (Leonard C., 2011)

In addition, it could be seen that the increased melting point of aged irradiated PS of 200kGy were lower than aged irradiated PS of 100kGy. The results were different from irradiated samples aged at constant 100°C. This was due to ramp aging did not provided as harsh as constant aging thermal condition effect on PS. It has been proved that relatively short chains tend to organize themselves into crystalline structure more readily than longer molecules (John, 2000). The chain scissioning network in aged irradiated PS of 200kGy did not undergo further chain scissioning during ramp aging. Thus, the melting point increased slightly compared to ramp aged irradiated PS of 100kGy.

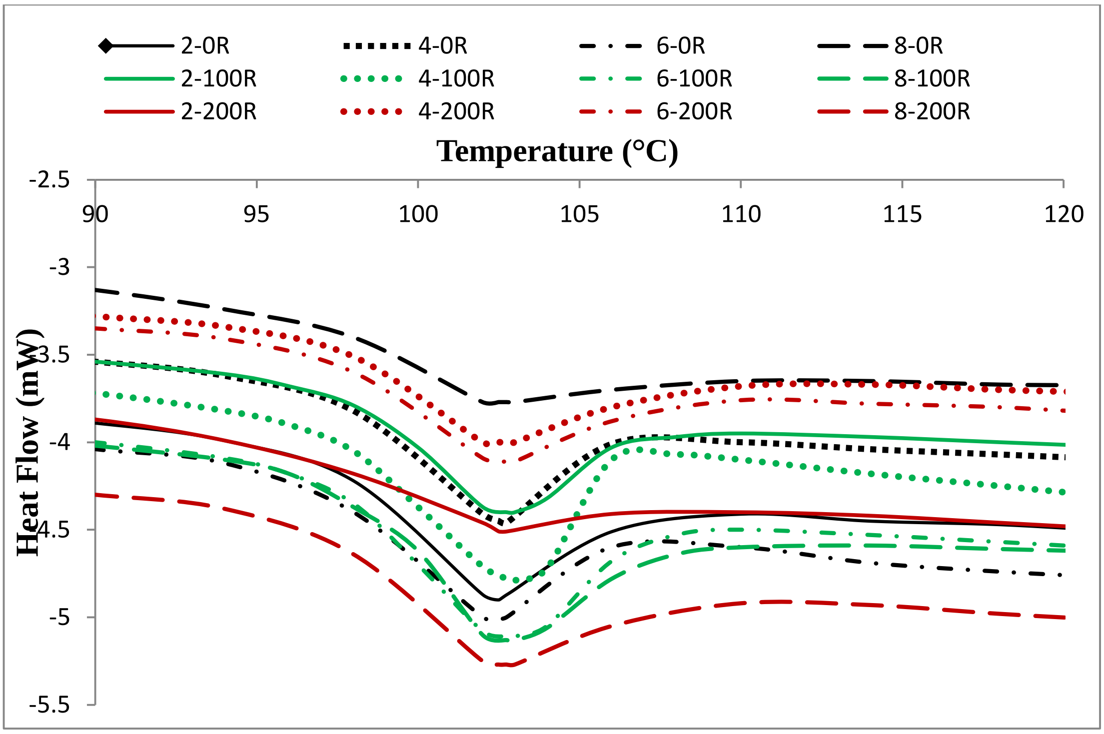


Figure 4.15: Differential Scanning Calorimetry (DSC) results of Irradiated PS Aged at Ramp 100℃

The enthalpy of melting data for various irradiated dose of PS samples for constant aging 100 ℃ and ramp aging 100 ℃ was obtained from the DSC thermograms and was plotted in Figure 4.16. It could be observed that the enthalpy of melting for irradiated PS aged at ramp temperature was higher than irradiated PS aged at constant temperature. This indicated that irradiated PS aged at ramp temperature required extra energy to break the bonds within the structure. Comparing irradiated PS without aging, the enthalpy of melting for irradiated PS aged at constant dropped significantly. The reason was because constant aging above T_g enhanced the thermo-oxidative degradation rate and cause chain scissioning and produced robustly crystalline. Hence, the energy required to break the bonds reduced. However, as discussed earlier, re-crosslinking occurred for constant aged irradiated PS of 200kGy. The enthalpy of melting remained lower than ramp aged irradiated PS was due to the re-crosslinked networks were weaker than original crosslinked networks.

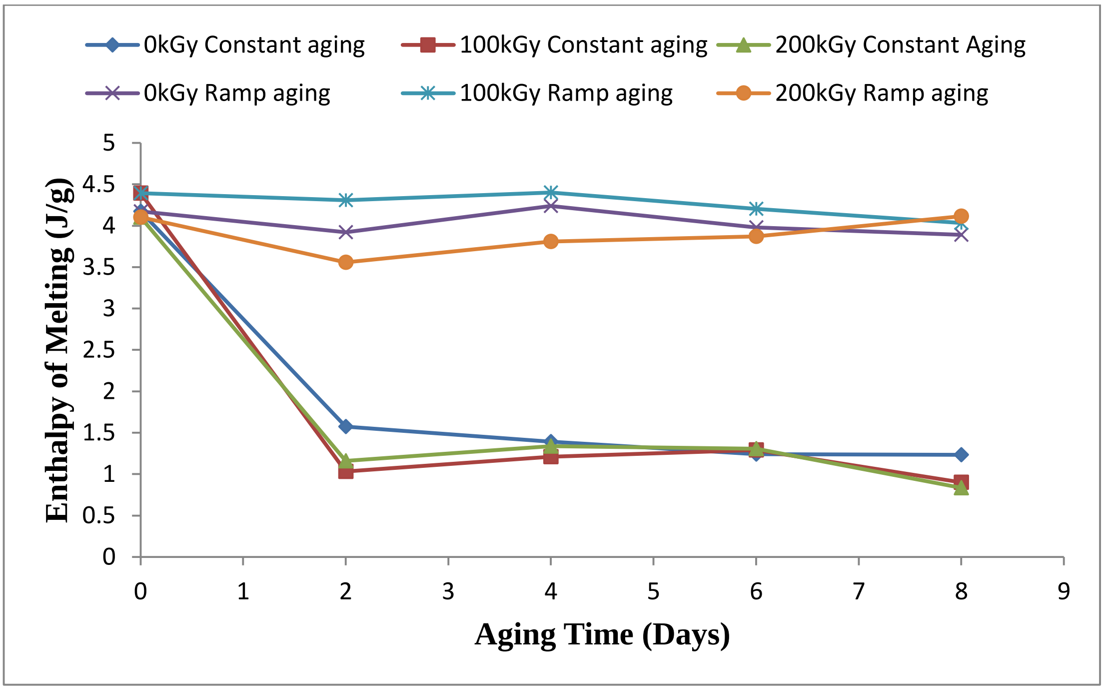


Figure 4.16: Enthalpy of Melting for Irradiated 100kGy PS Aged at Constant and Ramp 100℃

4.3 Physical Properties Analysis

4.3.1 Scanning Electron Microscopy (SEM)

SEM analysis was conducted in order to study the effects of electron beam irradiation on the surface morphologies of PS and thermal aging effects on irradiated PS. Apart from interaction of bonding, mechanical properties such as tensile strength, Young’s Modulus and elongation at break of the samples have been determined by investigating the types of morphological structures found in the irradiated PS and aged irradiated PS. Figure 4.17 showed the fracture surfaces of pure PS, irradiated PS at 100kGy and 200kGy. SEM test was conducted after the samples went through tensile test. Based on the Figure 4.17(b), PS irradiated with 100kGy showed smooth and continuous structure at the ruptured region. In other words, the matrix continuities of PS irradiated with 100kGy were seen to be the highest as compared to pure PS and PS irradiated with 200kGy electron beam. This could be attributed to the development of crosslinking networks at low irradiation dosage. With this particular morphological structure, PS irradiated with 100kGy electron beam was expected to possess good tensile strength and Young’s Modulus. Thus, PS irradiated with 100kGy has the highest tensile strength which is 36.4986 MPa.

Apart from that, from Figure 4.17(a) a crystal-like structure was seen on the fractured surface of pure PS. This indicated pure PS has high brittleness and very easy to break. Thus, as showed in the figure, pure PS has less elongation and caused it to break immediately right after a pulling forced was applied. However, it was also observed that PS irradiated with 200kGy showed voids and poor matrix continuities. This happened because high irradiation dosages caused chain scissioning effects on PS. As a result, the PS extendability increased. In other words, PS become more elastic and has highest elongation before breaking as observed from Figure 4.17(c). This observation is consistent with the result obtained in precious section where the elongation at break of PS increased significantly when irradiated with high irradiation dosages.

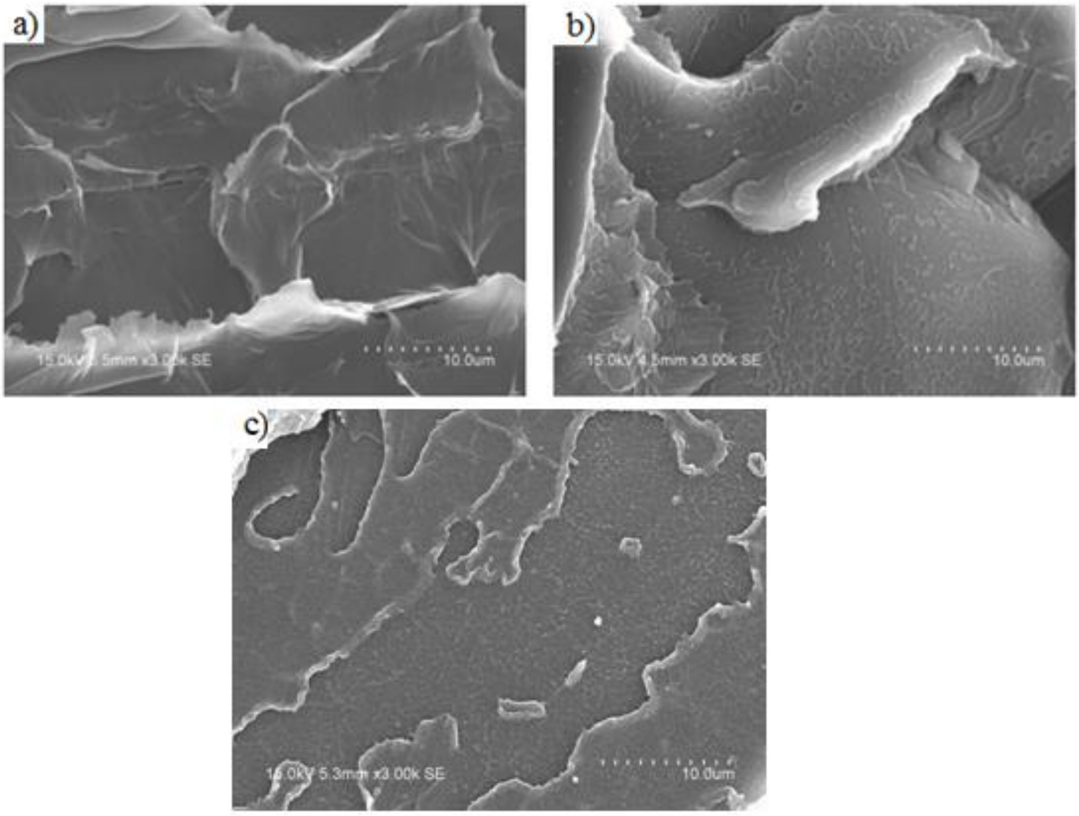


Figure 4.17: SEM Images for (a) Pure PS (b) 100kGy Electron Beam Irradiated PS and (c) 200kGy Electron Beam Irradiated PS

Figure 4.18 showed the fracture surfaces of pure PS, irradiated PS at 100kGy and 200kGy aged at constant 100℃ for 2 days and 8 days. From the figure it could observed that pure PS and irradiated PS showed changes in the surface morphology after constant aging. Figure 4.18(a) indicates aged 2 days pure PS showed a slight change in the surface morphology. From the figure, the aged PS has less crystalline structure compare to pure PS, Figure 4.17(a). This was due to constant aging above T_g of PS caused aged PS to become slightly elastic behavior as observed from the figure the elongation effect were larger than pure PS. On the other hands, Figure 4.18(c) indicates aged 2 days for 100kGy irradiated PS showed the matrix was less continuous compared to Figure 4.17(b). This was due to thermal degradation occurred during constant aging which indicated the decrease in tensile strength and higher elongation effect. Apart from that, it also found that from Figure 4.18(e) indicates aged 2 days for 200kGy irradiated PS has better matrix continuity than aged 2 days for 100kGy irradiated PS. The reason was because constant thermal aging caused thermal degradation in PS where the short chain produced due to chain scissioning effect when irradiated at high irradiation dosages to further chain scissioning and form shorter chains with low molecular weight. This enhanced the mobility of the chains and initiated the chains to recrosslink and formed a low energy crystalline state. Thus, aged 2 days for 200kGy irradiated PS were slightly brittle as observed from the figure due to less elongation. However, the matrix continuity was lesser than pure 200kGy irradiated PS because recrosslinking effects could not return the aged samples back to original states. Therefore, the mechanical properties remain poorer than pure irradiated PS and the results can be further supported by the results obtained from the mechanical test.

Besides, from Figure 4.18 (b), (d) and (f) showed that prolonged thermal aging caused formation of voids. This implies that more short chain polymers that formed during thermal degradation have been degraded and formed volatile gases. This voids caused irradiated PS to break easily. Hence, the irradiated PS aged for 8 days showed weaker mechanical properties compared to irradiated PS aged for 2 days.

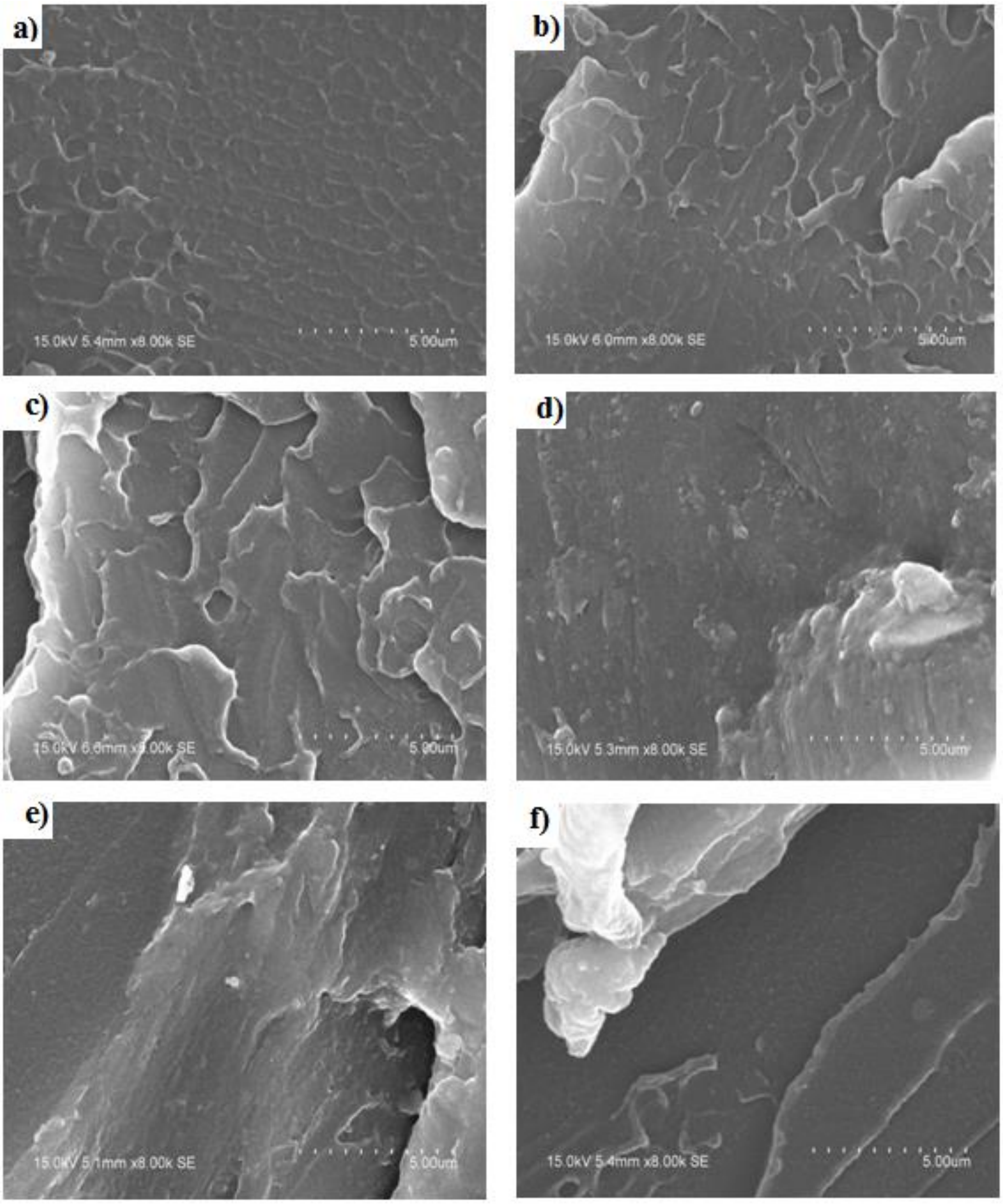


Figure 4.18: SEM Images for Pure PS Aged (a) 2 days and (b) 8days, 100kGy Electron Beam Irradiated PS Aged (c) 2 days and (d) 8 days and 200kGy Electron Beam Irradiated PS Aged (e) 2 days and (f) 8 days at constant 100℃

Figure 4.19 showed the fracture surfaces of pure PS, irradiated PS at 100kGy and 200kGy aged at ramp 100℃ for 2 days and 8 days. Figure 4.19(a) indicates aged 2 days pure PS showed a significant change in the surface morphology. From the figure, the aged PS has the poorest matrix continuity compare to pure PS, Figure 4.17(a) and constant irradiated PS, Figure 4.18(a). The reason was because of the large pendant group of PS. During cooling period, the pendant group reduced the mobility of chains and caused random packing into slight amorphous structures. Hence, the mechanical properties of PS such as tensile strength and Young's Modulus reduced. Besides, from the figure it could be observed that the elongation effect was larger. Comparing to aged 8 days pure PS from Figure 4.19(b), it have the weakest matrix continuity and elongation effect was much larger.

From Figure 4.19(c), indicates aged 2 days 100kGy irradiated PS it was found that the surface was smoother compared to pure PS and constant aged irradiated PS. This means that the matrix phase exhibited high level of continuity. This was due to thermal cycles increased the inter-chain interactions which attributed to crosslinking. Hence, this implies that 100kGy irradiated PS aged at ramp aging showed improved mechanical properties. However, aged 8 days 100kGy irradiated PS showed a degraded surface morphology with less matrix continuity and high number of voids. The high number of voids was due to recrystallization process during ramp aging. In other words, during the slow cooling rate, formations of voids occurred and thermomechanical stress dominated due to thermal cycling. These voids reduced the ability of PS to withstand pulling force and break easily, reducing the mechanical properties.

In addition, it was also found that from Figure 4.19(e), ramp aged 2 days 200kGy irradiated PS has better matrix continuity than constant aged 2 days 200kGy irradiated PS. This proved constant aging caused more severe damages than ramp aging. Besides, it could be observed that the elongation effect was much smaller during ramp aging than constant aging. This was due to ramp aging allow the irradiated samples to cool slowly caused formations of low energy state crystalline structure. However, Figure 4.19(f), ramp aged 8 days 200kGy irradiated PS showed an improved surface morphology. The matrix phase was smoother and exhibited high level of continuity. Thus, the elongation effect was low as observed from the figure. The reason was because shorter chains network produced from high irradiation dosages were underwent further breaking of chains after prolonged exposure to elevated temperature. These shorter chains caused recrystallization to occur and recrossliking effect due to enhanced mobility and slow cooling rate. Therefore, ramp aged 8 days 200kGy irradiated PS were expected to exhibit better mechanical properties and further proved by the results obtained from mechanical tests.

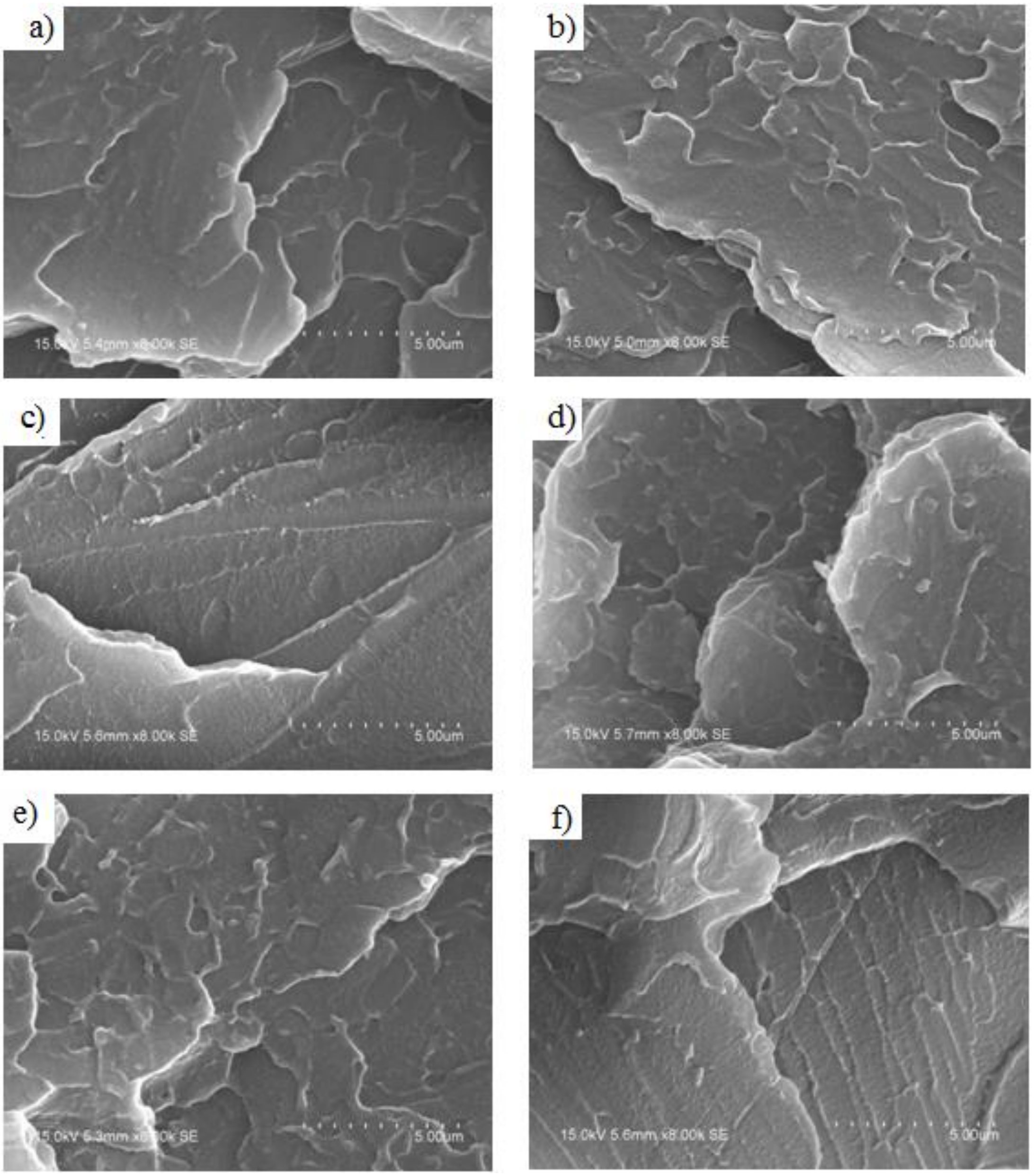


Figure 4.19: SEM Images for Pure PS Aged (a) 2 days and (b) 8days, 100kGy Electron Beam Irradiated PS Aged (c) 2 days and (d) 8 days and 200kGy Electron Beam Irradiated PS Aged (e) 2 days and (f) 8 days at ramp 100℃

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The change of irradiated PS under oven treatment in mechanical properties, physical properties and thermal properties has been studied and investigated after undergoing the corresponding analyses. The summaries for different properties are concluded in the following sections.

For the mechanical properties of irradiated PS, the tensile strength increased with irradiation dosages from 50kGy to 150kGy. The crosslinking networks produced by low irradiation dosages tend to increase the mechanical properties of PS. Further dose or irradiation decreased the tensile strength of PS due to the chain scissioning dominate over crosslinking. For the the Young’s modulus of the irradiated PS, the results showed similar trend with the results of tensile strength whereas the percentage elongation showed the opposite due to its brittle behaviours. The percentage of elongation at break decreased slightly from 12% % to 8.45 % and then increased to 15.2 %. The earlier decreased was due to crosslinking effect which restraint the pulling force and its brittle behavior. For the Young’s modulus, it increased from 110 MPa to 160 MPa and eventually decreased to 100 MPa when the chain scissioning occured. The initial increase was due to the rigidity of compound was enhanced due to crosslinking. In addition, the mechanical properties of irradiated PS were increased during ramp aging compared to constant aging where the mechanical properties were decreased. The reason was because constant aging tend to cause thermal degradation where as ramp aging provided a slow cooling rate causes re-crystallization process occurred.

For the thermal properties of the irradiated PS, melting point increased when irradiated at low irradiation dosages due to crosslinking effect increased the crystallinity of PS while PS irradiated with high irradiation dosages the melting point decreased due to crystalline structure degraded. For irradiated PS aged at both constant and ramp 100 ℃, Differential Scanning Calorimetry (DSC) analysis indicated that the bonding spectrum for irradiated PS aged at ramp conditions was narrower and sharper. For narrower and sharper bonding spectrum, higher energy was needed to enables the molecules of polymer to free out from the structure. Besides, the enthalpy of melting was higher for ramp aged irradiated PS compared to constant aged irradiated PS. This might be attributed by the stronger bonds in the irradiated PS ramp aged due to slow cooling effect.

For the physical properties of the pure PS, Scanning Electron Microscopy (SEM) analysis showed that brittle morphology was found while continuous morphology structure was observed when pure PS irradiated with low irradiation dosages due to crosslinking process. Meanwhile pure PS irradiated at high irradiation dosages showed a less continuous matrix due to chain scissioning. Thus, the mechanical properties of pure PS irradiated with low irradiation is better than pure PS irradiated with high irradiation. Besides, irradiated PS aged at constant elevated temperature caused the matrix to become less continuous. This caused the mechanical properties degraded such as tensile strength and Young’s Modulus which proved from mechanical test sections. However, compared to ramp aged irradiated PS, the surface morphology became better. The reason was because ramp aging allowed irradiated PS to cool slowly which increased the formation of crystalline structure. Thus, the mechanical properties and thermal properties of irradiated PS enhanced. Nevertheless, SEM also showed that prolonged heating of irradiated PS would degrade its surface morphology and increased the voids formation due to repeating of recrystallization process. This significantly reduced the mechanical properties and thermal properties.

5.2 Recommendations

It is recommended that blending of PS with other polymers and irradiation with electron beam can be carried out followed by thermal aging at different durations and different temperature to observe the changes of properties for PS blends. Besides, Transmittance Electron Microscopy (TEM) should be carried out in this research in order to verify the agglomeration of PS blends with other polymers. (Luty, Molefi and Krump, 2006).

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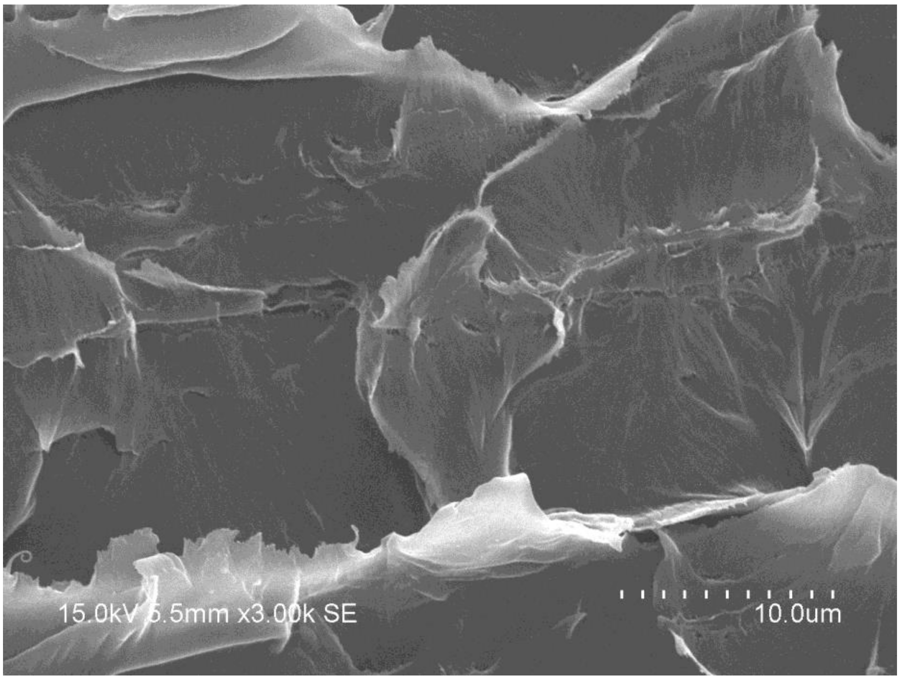
APPENDICES

APPENDIX A: Turnitin Originality Report

APPENDIX B: SEM Images



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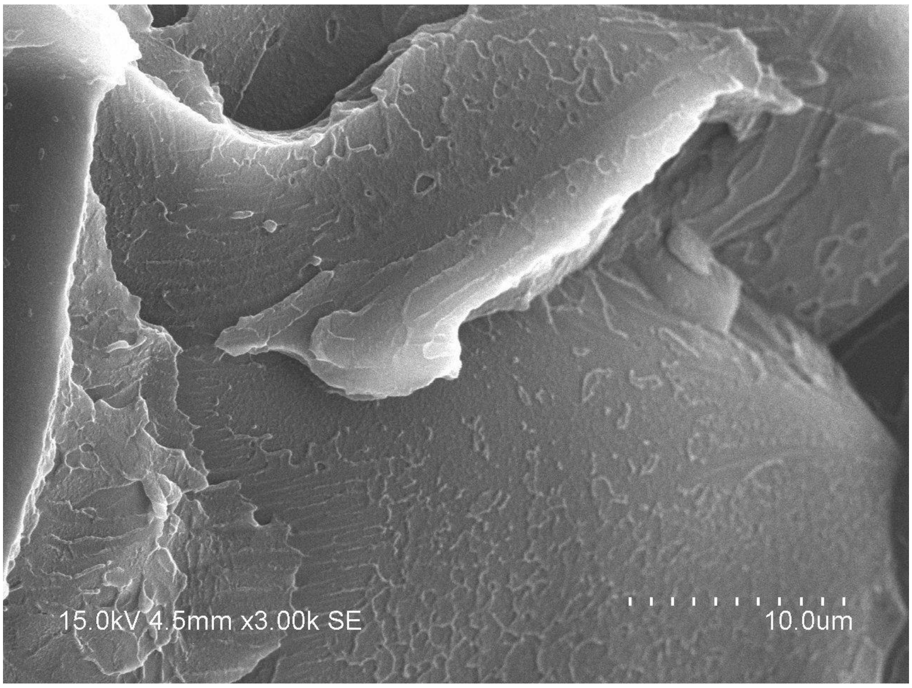

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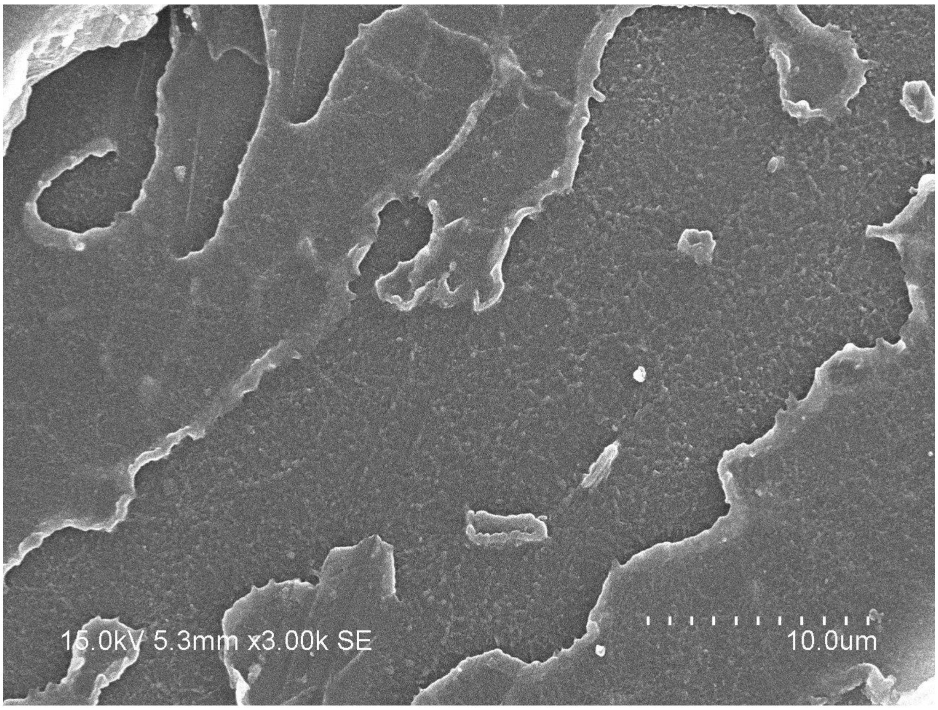

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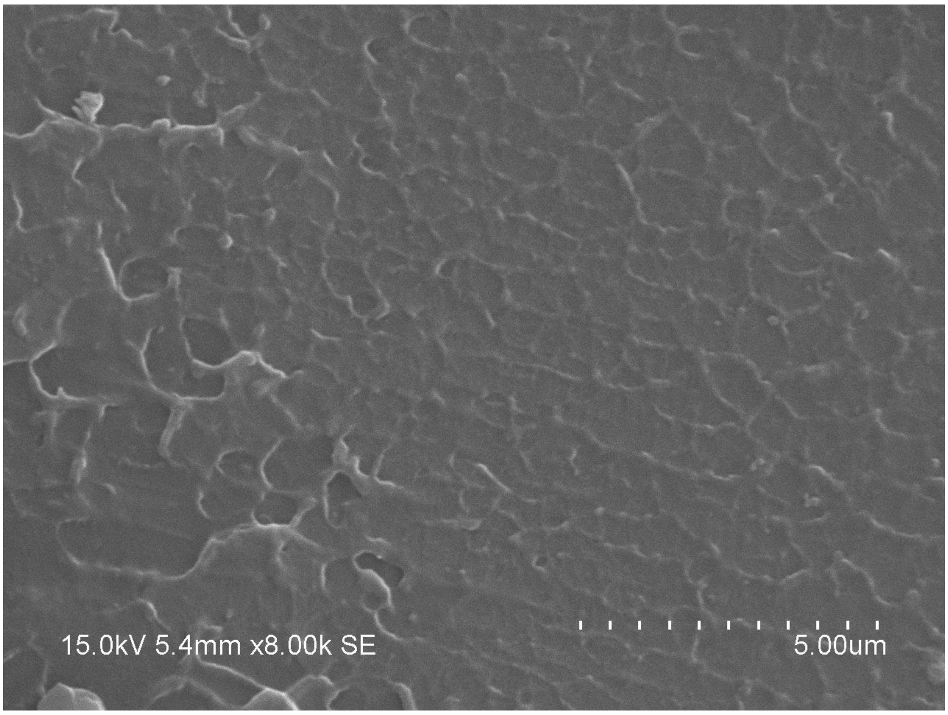
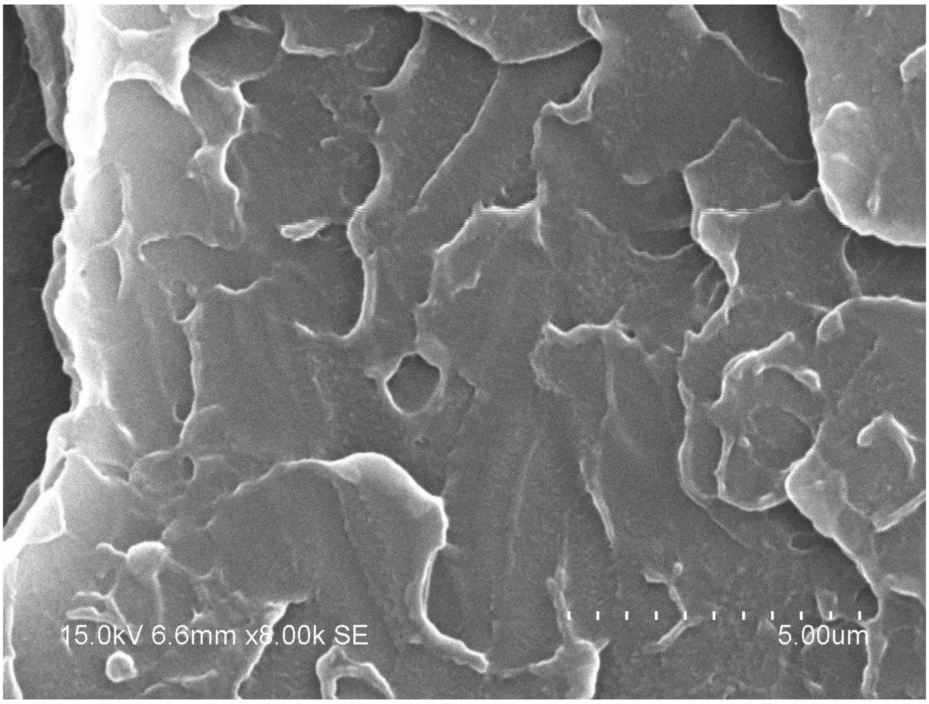


Pure PS Aged 2 days at constant 100℃



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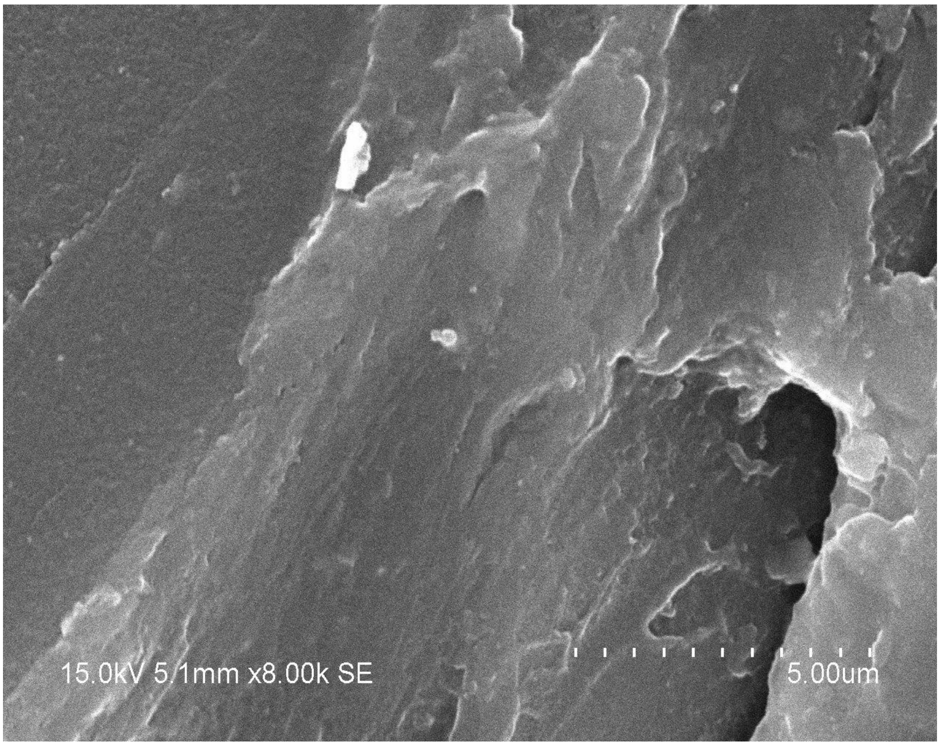

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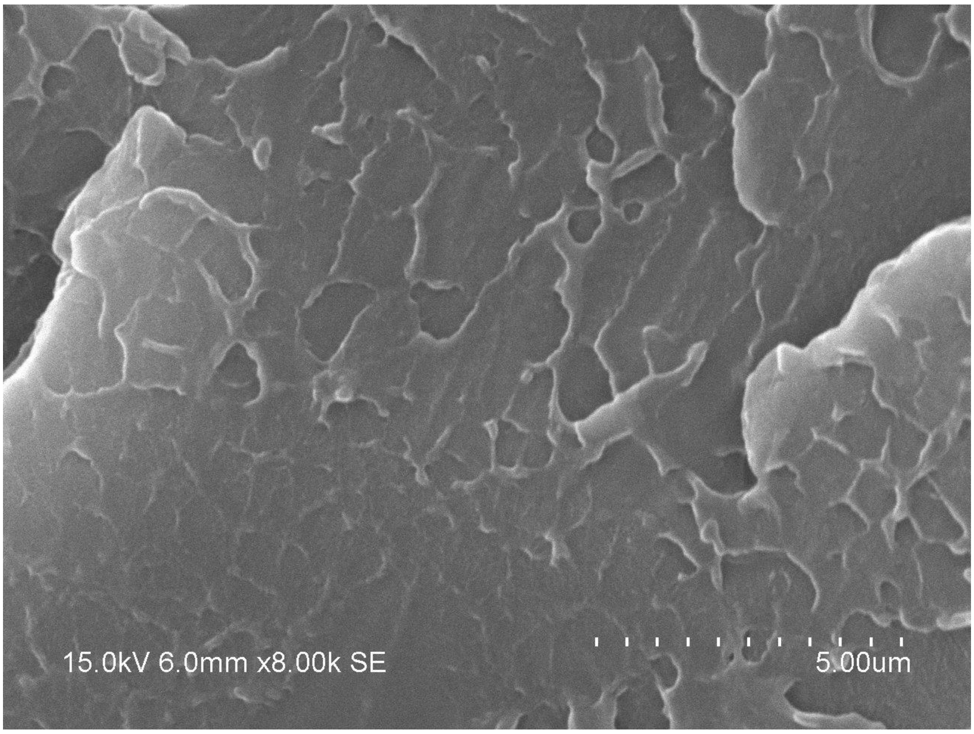

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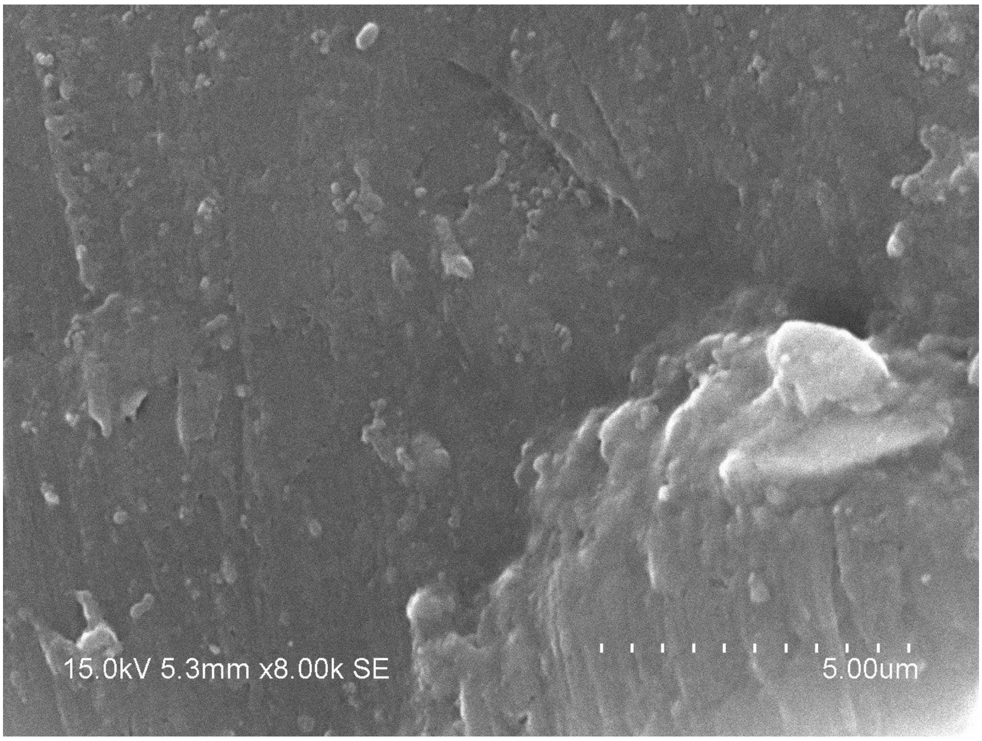

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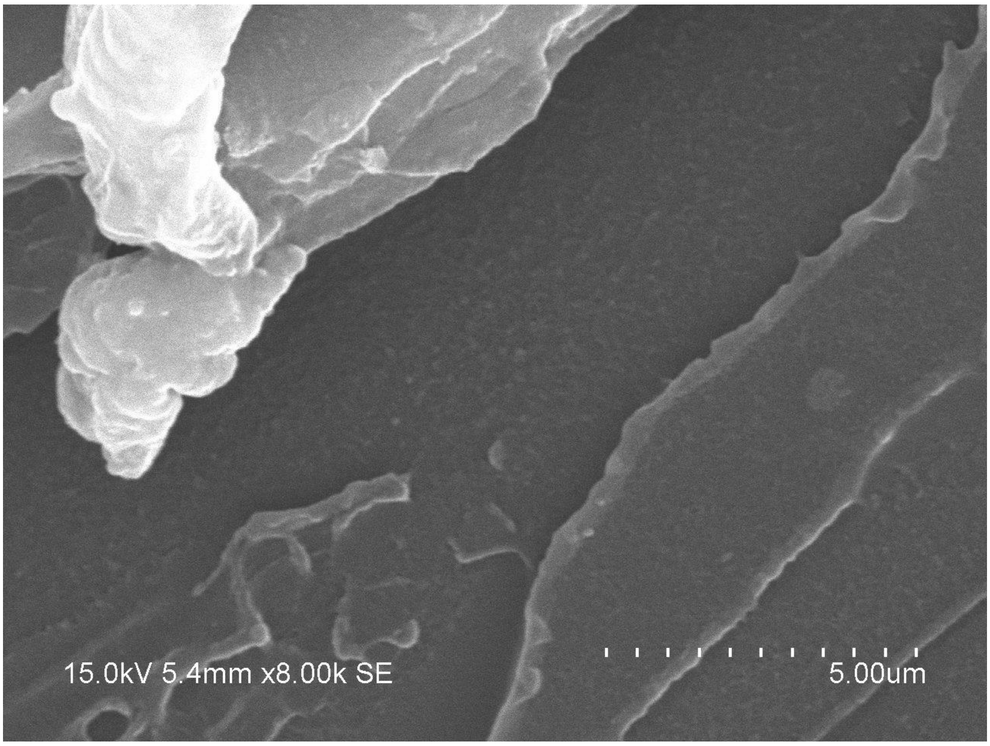

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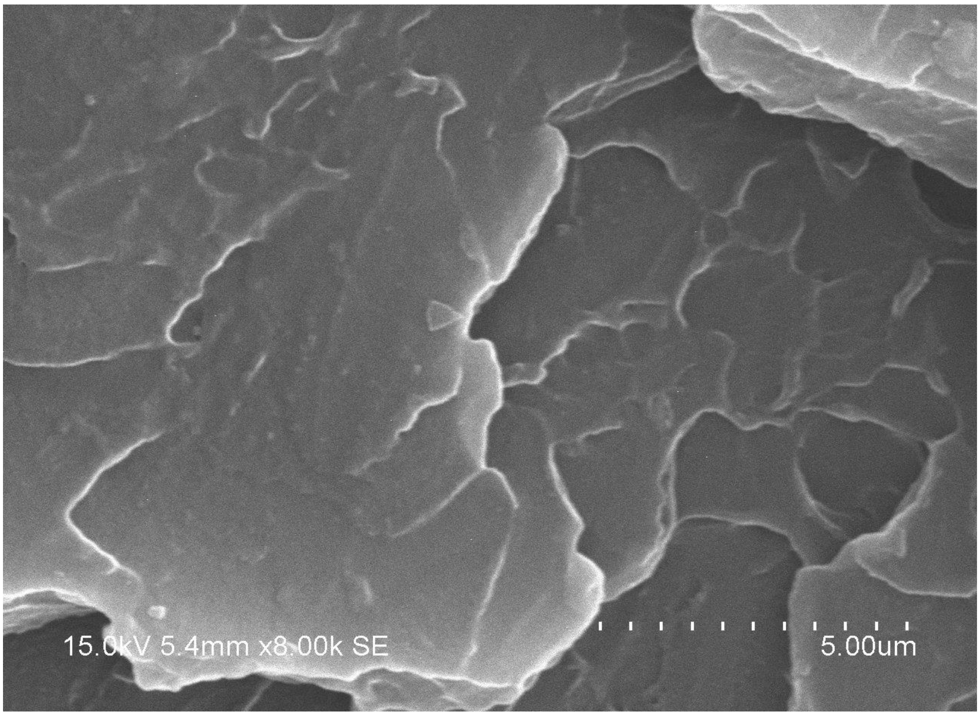
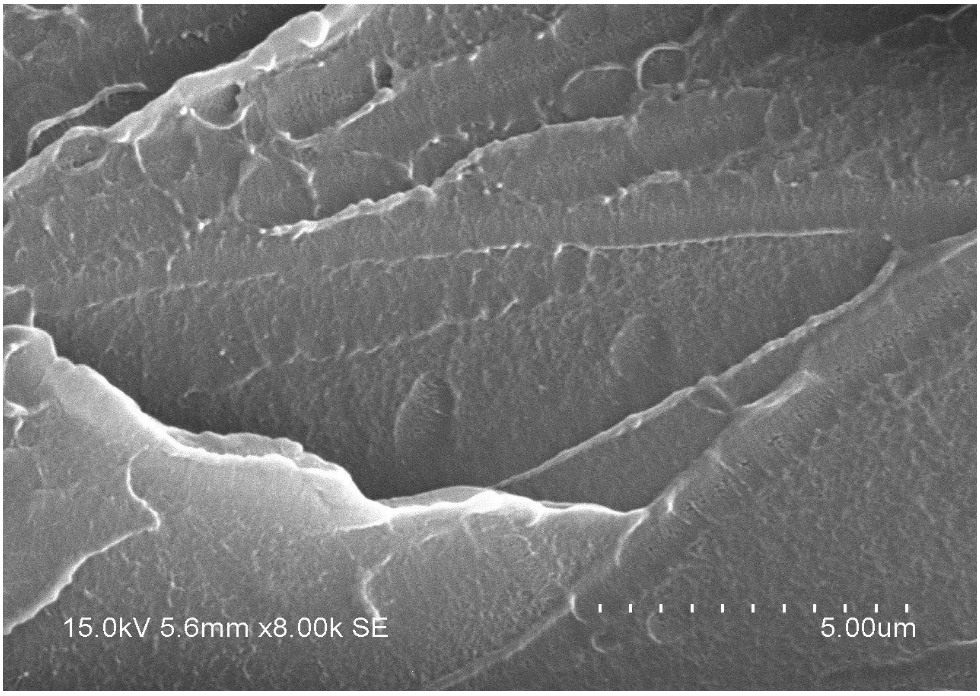


Pure PS Aged 2 days at ramp 100℃



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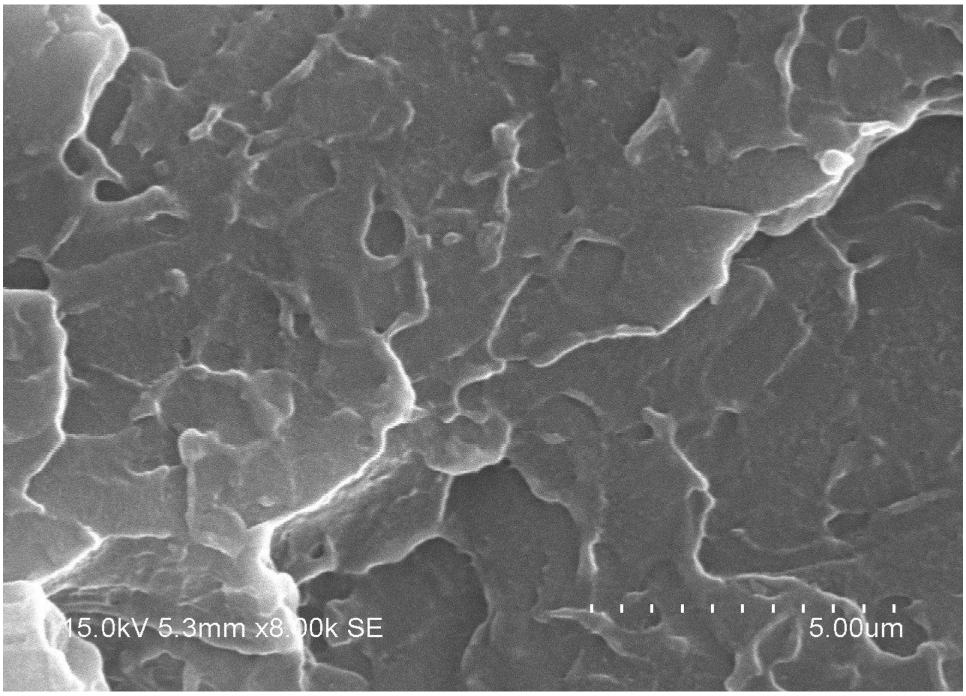

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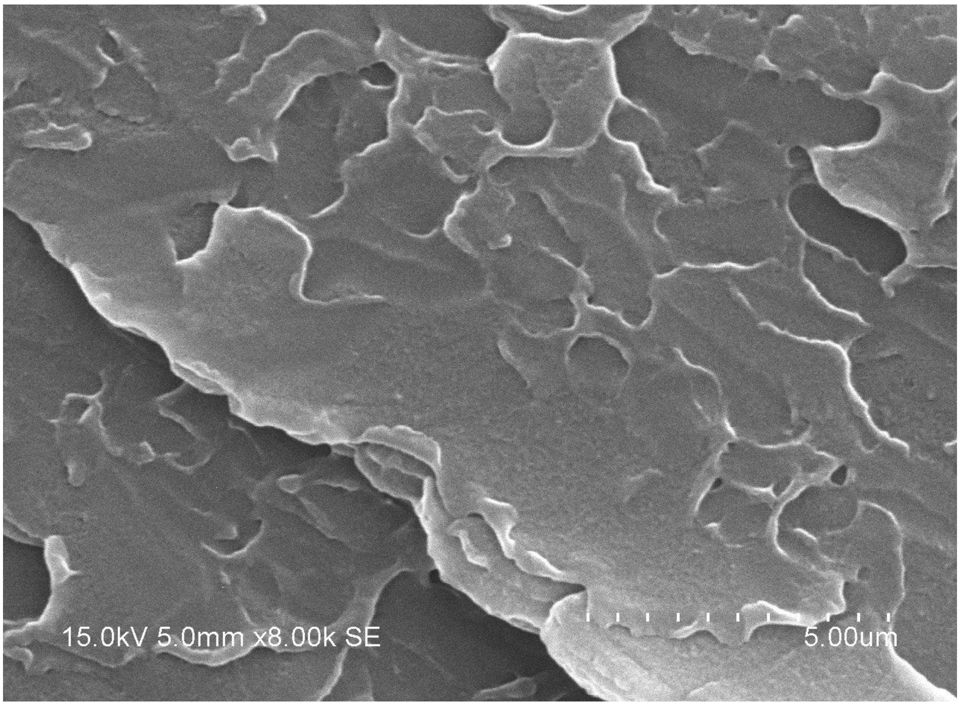

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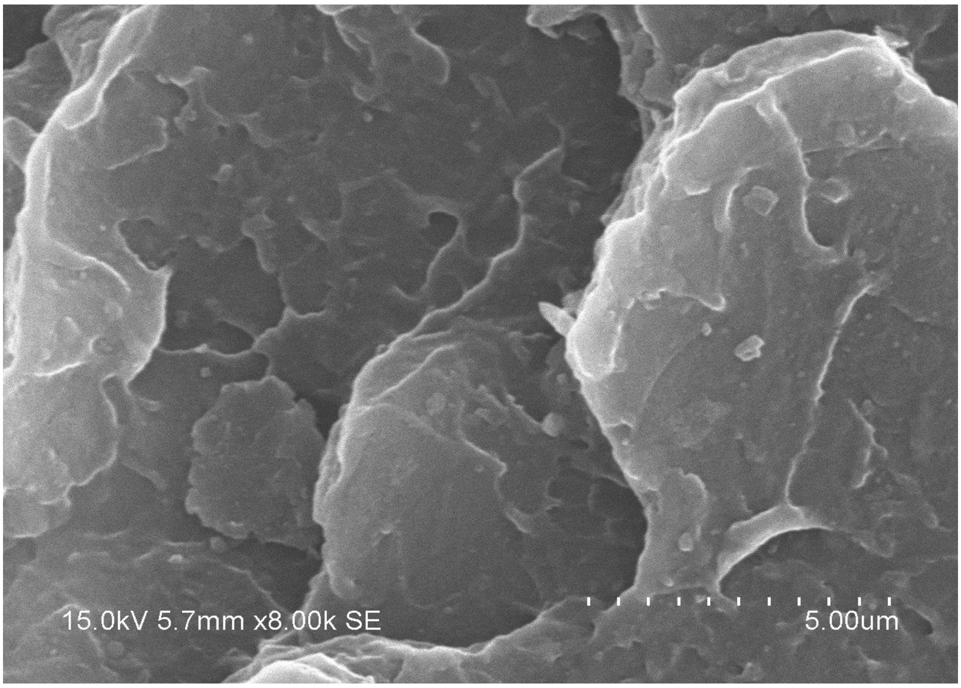

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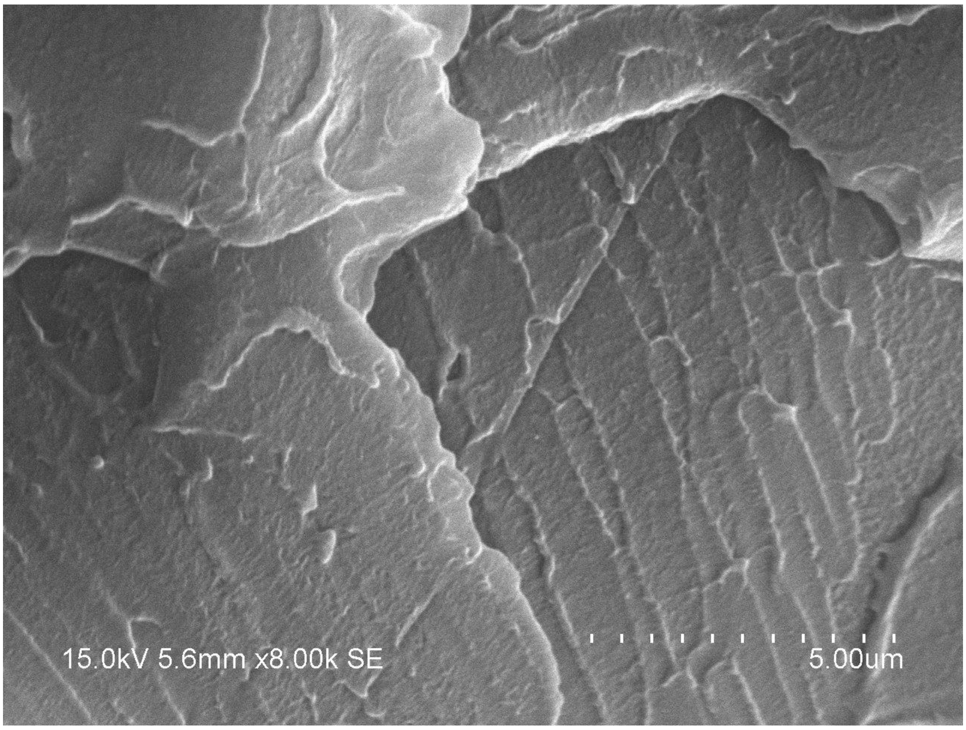

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