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RESEARCH ARTICLE

Feasibility study of small core diameter polymeric optical fibers (POF) from poly(methyl methacrylate)

Amirul Afiat Raffi [a], Mukhlis A. Rahman [a,*], Mohd Hafiz Dzarfan Othman [a], Ahmad Fauzi Ismail [a], Noriah Bidin [b], Norhana Yahya [c]

[a] *Advanced Membrane Technology Research Centre (AMTEC), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*
[b] *Laser Centre, Ibnu Sina Institute for Industrial and Scientific Research (ISISIR), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*
[c] *Department of Fundamental and Applied Science, Universiti Teknologi Petronas, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia*

* *Corresponding author: r-mukhlis@utm.my*

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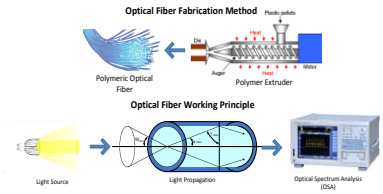
Graphical abstract



Abstract

This work describes the fabrication and evaluation of small core diameter Polymeric Optical fibres (POF) prepared from Poly(Methyl Methacrylate) (PMMA). Based on prior study, POF has a very interesting property in terms of short-reach local area networks due to the simpler manufacturing process and inherent immunity to electromagnetic interference and radiation. It can overcome the limiting factors of conventional glass-based optical fibre in terms of cost-effective, flexibility and easy installation. This study focused on introducing effective fabrication method to produce small diameter PMMA POF core using extrusion process. Prior to extrusion, we managed to produce PMMA cores with diameters of 650 µm, 750 µm and 850 µm. Based on the outcome of this study, the drawing tension and extrusion temperature have been identified as major influences on core diameter. The SEM images indicated that dense structure and clean surface whereas DSC and TGA analyses revealed that almost similar glass transition temperature and degradation weight loss in between fabricated PMMA core and industrial polymer optical fibre.

Keywords: Polymeric, optical, fiber, POF, PMMA

INTRODUCTION

The optical fibre has been used in transmitting various information from internet services, a telecommunications network, local area networks and others [1]. The demand for high-speed internet communication grows explosively as the demand for data volume in a personal devices increases in term of internet video images, in particular such as the 8K ultra high definition and online face-to-face communication [2]. Based on the Internet Traffic Statistic Archive (ITSA) developed by Hoogesteger et al. (2016), the data from The Brazilian National Research and Educational Network (NRP) recorded an increment about 12.1 % of port distribution from week 49 in 2013 until week 35 on 2015. This gradual increase in usage reflects as more internet user growth year by year. A similar trend can also be observed among internet users in Malaysia whereas data reported by Malaysian Communications and Multimedia Commission (MCMC) showed an increase up to 11% of internet users from the year 2014 to 2015. The trend shows that the demand for high bandwidth communication has boosted the research and development of optical fibres, the future perspective of the optical fibres in form of ultra-high capacity transmission. To address the demand for high bandwidth communication systems, the development of optical fibres is started with ultra-thin glass optical fibres that have a core diameter of 8 to 10 µm. Silica glass optical fibres can undeniably achieve extremely high data rate and long-distance communication. However, they require a precise and time-consuming technique for cable production, termination, connection, and branching because of their small diameter that less than 10 µm, which induces higher cost for LAN system that required plenty numbers of connections and junctions [4].

Therefore, developments of polymer-based optical fibres (POFs) will overcome the limiting factors of glass-based optical fibres, in a way of cost-effective, flexible and easy to install because of larger fibre core diameters up to 1000 µm. Furthermore, optical fibres show a complete immunity to electromagnetic interference and radiation compared to the previous copper communication cable. Although POF exhibits higher attenuation, current research is projected towards producing POF with lower dispersion, lower attenuation, excellent flexibility in term of mechanical strength and optical ability that able to cope with high temperature and pressure operation. There are several types of POF such as single-mode, multimode, double Step-Index, multi Step-Index, multi-core, step-index, and graded-index. Step-index (SI) optical fibre consists of core and cladding section, whereas core is made from a polymer that has slightly higher refractive index than cladding coating. As mentioned by Ab-Rahman et al. (2010), the cladding materials are usually made out of fluorinated polymer from the same monomer as core to create strong adhesive interaction between core and cladding. Recent development in step-index (SI) polymer based optical fibres is lacking in term of the long-distance system due to higher attenuation problem existing within the polymers optical itself. According to the previous study by Atef et al. (2011), they able to achieve transmission speed up to 170 Mb/s for multilevel transmission over 115 meters of standard SI polymer optical fibre using multilevel pulse amplitude modulation (M-PAM). Another study by Atef et al. (2012), they achieved 1.25 Gbit/s transmission speed over 50 meters of SI POF using a fully integrated equalizer as an optical receiver. The source of attenuation in optical fibres can be divided into two groups which are intrinsic and extrinsic attenuation. Attenuation of fibres determines the maximum transmission distance of optical communication systems

since the optical intensity of the light will decrease during transmission in a straight fibre because of various absorption, scattering, and radiation mechanisms. Latest advancement on polymer fiber based in step-index polymer is used on short distance optical waveguides into tissue or organ using biodegradable citrate-based POF[8]. Latest glass optical fiber based on step-index approach by Galleani *et al.* (2017), able to produce core with 68 µm diameter using drawing tension from built-in casting technique. Figure 1 shows the schematic diagram of extrusion

In this work, poly (methyl methacrylate) (PMMA) was chosen as core material for step-index (SI) optical fibres fabrication using extrusion process. Figure 1 shows the schematic diagram of PMMA core extrusion using polymer extruder. PMMA provides excellent benefits over the glass fibre with excellent flexibility, resilient to bending, high glass transition temperature, and easy to handle and install. The objective of this paper was to investigate the feasibility study using poly (methyl methacrylate) (PMMA) for small diameter Step-index polymer optical fibre in terms of surface morphology, physical, mechanical and optical properties.

EXPERIMENTAL

Materials

Poly (methyl methacrylate) (PMMA) polymer bulk pellets were obtained from Sigma-Aldrich® with an average molecular weight percentage of 120,000 g/mol and dried under 24 hours of drying at 80 ^{o}C using the oven with enhanced air circulation in order to ensure the water trapped inside PMMA bulk pellet was evaporated to reduce the effect of relative humidity towards optical long-term degradation performance [10]. Conventional industrial grade Step-Index Polymer Optical Fiber made of fluorinated polymer substrate core was obtained from Edmund Optic with diameter of 250 µm and 500 µm.

Fabrication of PMMA core

Poly (methyl methacrylate) polymer core was obtained using the batch polymer extrusion process by heat drawing of the preform. Dried PMMA polymer bulk was then melted using twin screw polymer extruder at a temperature of 220 ^{o}C with extruder screw speed at 17 RPM. The melted polymer was flowed across 1 cm diameter die head and cooled to room temperature using collector. Based on numerous extrusion testings conducted using 1 cm die head, the most suitable range for fibre collector speed was in between 4 RPM until 10 RPM, if more than that possibility of fibre to break during collection was high. The different diameter of the polymer core was obtained by manipulating the collector drawing speed tension to 4 RPM, 6 RPM and 7 RPM. The PMMA polymers cores samples with the designation of 650 µm, 750 µm, and 850 µm were obtained as summarized in Table 1.

Table 1 Details on PMMA core fabricated and industrial grade.

Sample	Diameter (µm)
PMMA 1	650
PMMA 2	750
PMMA 3	850
INDUSTRIAL 1	250
INDUSTRIAL 2	500

Characterization study

The scanning electron microscopy (SEM) (Hitachi, S4700 Japan) was used to characterize the morphological structure of SI PMMA POF. The field emission scanning electron microscopy (FESEM) (JEOL JSM-5610LV) was used to characterize the diameter of optical fibre core and cladding. The fibre was snapped using a special tool to reduce the surface crack and maintain the shape of POF. The POF sample was then coated with Au-Pd to enhance the morphological structure. This analysis was carried out using accelerating voltage of 15kV. In this study, DSC analysis was used to identify glass transition temperature of the polymer after heat modification from extrusion process and compare it with industrial fibre. Glass transition temperature (T_g) was measured using DSC 3 Mettler Toledo with a heating rate of 10 ^{o}C/min under nitrogen gas. Shimadzu TGA50 thermogravimetric analysis (TGA) was used to identify the changes in physical and chemical properties based on degradation mechanism and derivative thermogravimetric analysis.

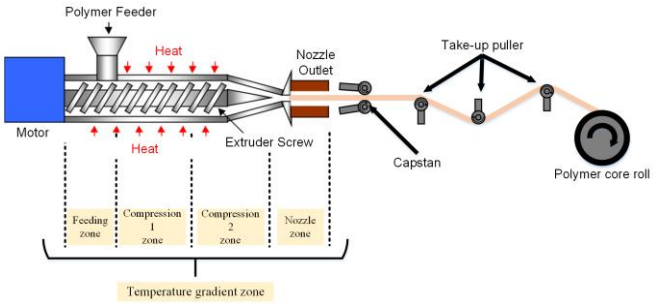


Fig. 1 Schematic diagram for fabrication of PMMA core using polymer extruder.

To measure optical fibres strain sensitivity, the fibre was subjected to a pure axial strain tensile test. The tensile strength of the fibre was evaluated by continuously measuring the force that developed as the sample was elongated at a constant rate of extension. The method followed ASTM D638 standard and tested using Instron 5567. The load frame was used to test the sample with a fixed speed of motorizing power screw at 2mm/min. To avoid any bending induced on the sample during tensile strength test, a special gripping system was used for polymer optical fibres to avoid fibre breakage at the end of the contact. To get an average reading of tensile test each sample, 5 numbers of trial with 5 cm gauge length were used. All the tests were carried out at room temperature.

RESULTS AND DISCUSSION

Morphology studies

Figure 2 shows the surface morphology of the cross-sectional and surface image of SEM analysis for fabricated PMMA polymers core and industrial grade fabricated. The SEM cross-sectional image of PMMA polymers cores was used to determine cores diameter with 120x magnification image. From Figure 2, the result indicated that there was no surface imperfection on all three fabricated and two industrial samples. Among the 3-fabricated sample, in figure 2(a), sample with 650 µm diameter showed clear surface images without micro crack or pore formation compared to figure 2(b) and 2(c) which have slightly rougher surface and minor crack. However, the image of cross-sectional diameter did not exhibit clean end-face surface due to the sharpness of cutting tools and pressure exerted during cutting. It was found that the optimal fabrication stretching was at 6 RPM, based on smaller 650 µm diameter produced. Figure 3 shows the cross-sectional image of surface interaction between core and cladding of industrial fabricated PMMA optical fibre. From Figure 3(a) and 3(b), both industrial fabricated optical fibres consisted of 10 µm thickness cladding which was made from fluorinated polymer. Theoretically, attenuation is depended on fibre core diameter, as the core size becomes smaller, the extrinsic attenuation increases due to a greater number of geometrical and structural imperfections that leads to radiation losses such as *microbends* and *macrobend* bendings [11]. It is possible to reduce the control of the extrinsic attenuation and reduce intrinsic attenuation of smaller diameter fibre by controlling the molecular vibrational absorption, intermodal dispersion, and chromatic dispersion.

Thermal properties study

Differential Scanning Calorimetry (DCS) analysis was used to identify the thermal properties of PMMA cores. The measurement was conducted with sample weight of 6.300 mg, a heating rate of 10 ^{o}C/min and at a temperature ranging from 30 to 400 ^{o}C. In DSC analysis, the glass transition of PMMA polymer cores was observed as steep decrease in heat capacity of a sample during the heating due to the

enhancement of molecular motion in the polymer[12]. The first exothermic phenomenon occurred at a temperature around 122 °C was assumed to be the evaporation of unreacted monomer as that temperature might be above the glass transition temperature of the MMA monomers. Figure 4 represents the DSC analysis of 650 µm, 750 µm, and 850 µm of PMMA cores together with 250 µm and 500 µm industrial grade polymeric optical fibres. At the first region of Figure 4, the behaviour temperature analysis was linear and consistent until first eutectic melt caused by impurities at temperature 41.5 °C, before achieving phase transition to first glass transition temperature (Tg) at 102.8 °C for the sample 650 µm, 750 µm, and 850 µm. For the industrial sample 250 µm and 500 µm, the first glass transition temperature was at 114.3 °C. DSC measurements showed that the industrial sample glass transition was higher than fabricated polymer core due to fluorine element.

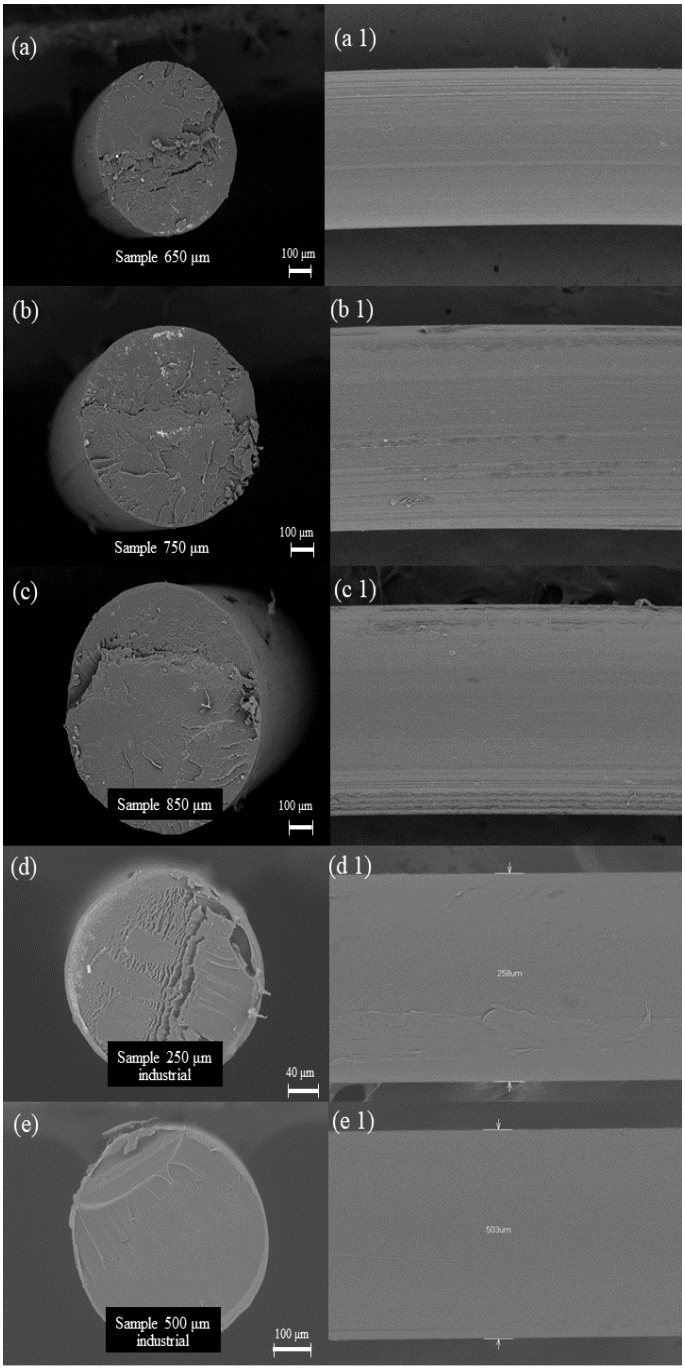


Fig. 2 The morphologies image diameter and surface cross-sectional images of PMMA polymer at (a & a1) 650 µm, (b &b1) 750 µm, (c & c1) 850 µm, (d & d1) 250 µm industrial sample and (d) 500 µm industrial sample.

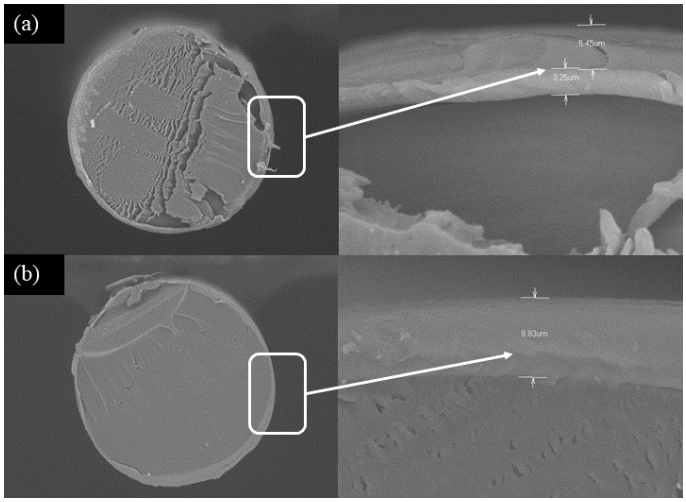


Fig. 3 The morphologies images of industrial grade PMMA polymeric optical fiber (a) 250 µm cross-sectional view and core/cladding interaction (b) 500 µm cross-sectional view and core/cladding interaction, (c) 250 µm surface image and (d) 500 µm surface image.

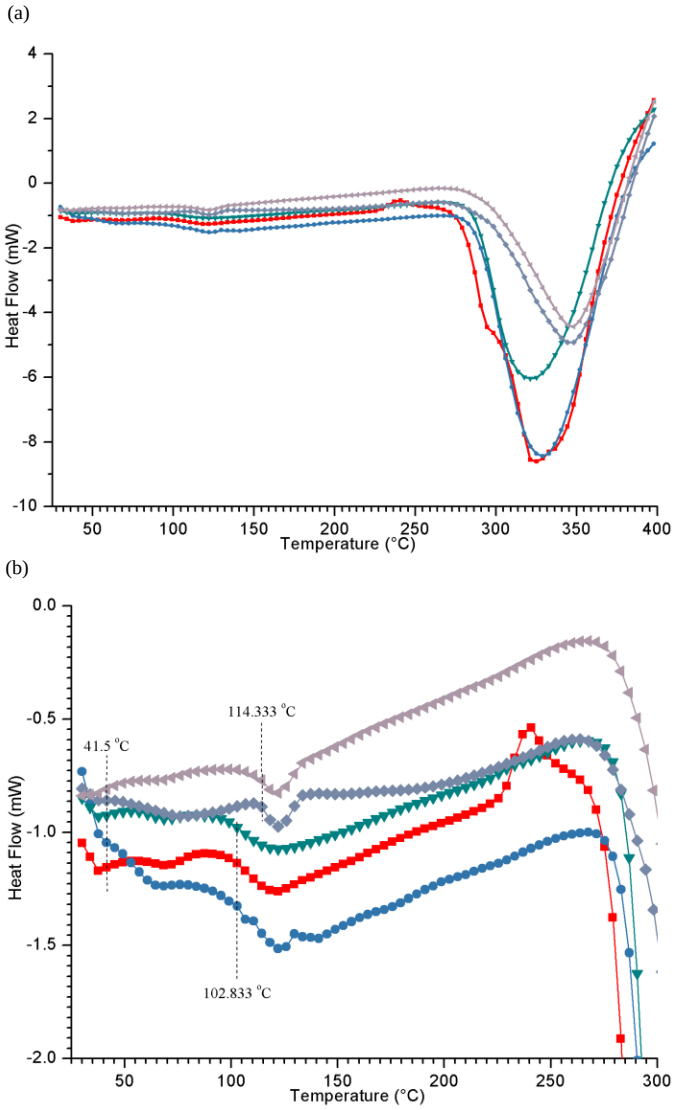


Fig. 4 Thermal analysis for DSC glass transition (a) temperature 30 °C to 400 °C and (b) temperature 30 °C to 300 °C [= 650 µm, = 750 µm, = 850 µm, = 250 µm and = 500 µm].

Thermogravimetric analysis (TGA) was used to analyse the physical degradation of PMMA core. Figure 5 shows the thermal

analysis in terms of weight loss thermogram (TG) and derivative thermogravimetric analysis (DTG). This technique literally provides the information on thermal degradation initiated by the scission of weaker links. Theoretically, degradation process of PMMA polymer is started with end-groups and random scission, followed by a de-propagation step and the first order termination reaction [13]. The data was recorded at a temperature ranging from 30 ºC to 500 ºC under nitrogen gas with the heating rate at 10ºC/min to determine weight loss pattern of PMMA core. Figure 5 depicts the thermogram of fabricated PMMA core and industrial PMMA optical fibre, a closer analysis of DTG curve showed that degradation process in nitrogen was occurred in two steps.

From Figures 5(a), weight loss started to occur at 300 ºC and about 50 % of weight loss occurred at 373 ºC. According to Ferriol et al. (2003), theoretical DTG weight loss curves are expected to have four stages starting around 165 ºC, 270 ºC, 350 ºC and in between 350 ºC to 400 ºC. From the DTG thermogram, the first weight loss mechanism occurred at 141.2 ºC initiated by scissions of head-to-head linkages hydrogen bonds (H-H). Second degradation step occurred at 271.7 ºC as it initiated by the scission at unsaturated ends involving a homolytic scission. The study conducted by Manring (1988) reported the third step degradation of PMMA unsaturated portion is in between the temperature of 230 ºC to 300 ºC. Based on Maring (1988), degradation happens due to β-scission of weak C-C bond β to the vinyl group. The last step of degradation process of our samples occurred in between 370 ºC to 380 ºC, it was initiated by homolytic scission of methoxycarbonyl side group followed by β-scission.

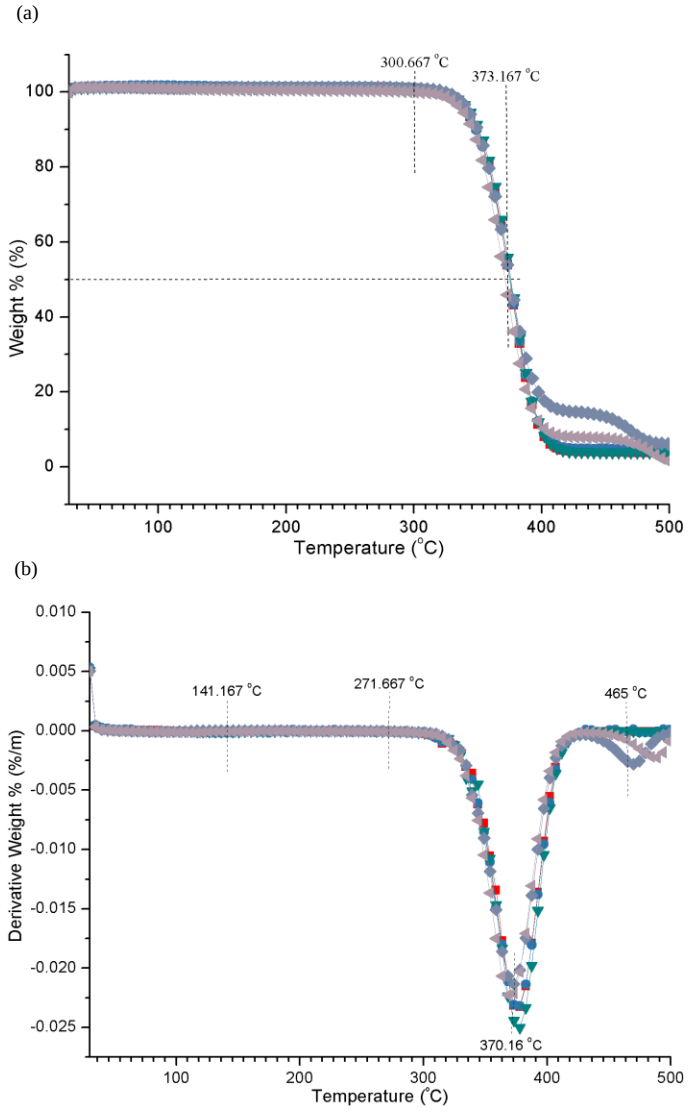


Fig. 5 Thermal analysis for (a) TG weight loss thermogram and (b) DTG derivative thermogravimetric analysis. [= 650 µm, = 750 µm, = 850 µm, = 250 µm and = 500 µm].

Mechanical strength studies

For polymer optical fibres, mechanical analysis study was focused on the attenuation effect induced by the bends and tensile stresses. The variation of stress-strain data between each sample contributed from molecular weight distribution during fibre drawing processes. The average stress of 650 µm was 136.28 MPa at 4.20% strain, the average stress for 750 µm was 64.23 MPa at 3.35% stress, the average stress for 850 µm was 45.70 MPa at 5.52% strain, the average stress for 250 µm was 59.88 MPa at 4.17% strain and the average stress of 500 µm was 46.93 MPa at 2.57% stress. It can be observed as the internal stress increased from higher drawing speed, it reduced the tensile strength at a certain point after optimum value of 650 µm in our range of testing. The average maximum tensile stress and Young's Modulus for fabricated fibres were shown in Table 2.

Table 2 The average tensile stress of fabricated and industrial samples.

Sample	Diameter (µm)	Maximum Tensile Stress (MPa)	Young Modulus (MPa)
PMMA 1	650	136.28	433.44
PMMA 2	750	64.23	171.89
PMMA 3	850	45.70	191.80
INDUSTRIAL 1	250	59.88	172.73
INDUSTRIAL 2	500	46.93	78.14

From the mechanical strength data, it showed that the fabricated PMMA core with 650 µm has the higher tensile strength and young modulus compared to industrial sample made of the fluorinated substrate. As mentioned by Peters (2011), the mechanical strength of optical fibres is strongly depended on fibre drawing process, drawing ratio between the preform and final fibre, extruder temperature, and speed.

CONCLUSION

The feasibility study of polymeric Poly (methyl methacrylate) (PMMA) for polymer optical fibre was successfully done. The fabricated PMMA cores were successfully prepared using extrusion process and were characterized together with two industrials samples made of the fluorinated substrate in terms of surface morphology, thermal analysis and mechanical strength. The diameter of fabricated polymer cores using extrusion process was affected by extruded temperature and drawing speed. In term of morphology study, there was similarity in term of surface roughness of the fabricated polymer core and the industrial one. As well as thermal analysis, the differences in terms of glass transition and degradation analysis of fabricated polymer and industrial were almost the same. However, there was different in term of mechanical strength between the fabricated polymer and the industrial one, which might be different due to the diameter of polymer fibre and molecular weight distribution. A considerably high tensile strength and young modulus of 650 µm fibre showed that it is feasible to use PMMA for further fabrication of even smaller diameter polymer optical fibre core. Next phase of the study will involve the surface interaction of synthesized PMMA 1, 2 and 3 cores with cladding in order to have total internal reflection inside fibre core.

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