Effect of Fabrication Techniques, Resin Types and Fiber Combinations on Mechanical Properties and Morphology of Glass Fiber Composites

Onny Ujianto, Afid Nugroho, Hendro Sat Setijotomo, and Atik Bintoro

***Abstract*—Glass fiber composites were fabricated from two different manufacturing techniques, vacuum infusion and vacuum bag, two resin types (epoxy, vinyl ester), as well as and two fiber combinations (S-glass and E-glass). The analyzed properties were tensile modulus, strength as well as compression strength, with relation to sample morphology and fracture surface due to compression. The results showed that all variables and their interaction did not significantly influence tensile modulus, while manufacturing methods was the only significant variable influenced tensile strength. The results showed that vacuum infusion samples had better tensile strength than those produced by vacuum bag due to less resin and bubbles. In term of compression, the change on strength was highly contributed by resin type and fiber used on layer A. Composites samples with epoxy resin showed better strength than those of vinyl ester may be due to better initial resin property. While, imbalance transfer load and fiber density inhibiting resin penetration and causing resin rich samples produced lower compression strength for samples with S-glass applied to layer A than E-glass. Further analysis on fracture surface showed that most samples failed on compression test due to shear, kink and resin break.**

***Index Terms*—Infusion, vacuum bag, epoxy, vinyl ester, mechanical, morphology.**

I. Introduction

Polymer matrix composite materials are commonly used in transportation as aerospace, trains, cars parts due to its lightweight that reduces fuel consumption and increase travel distance. It can be produced with fiber reinforcement as carbon or glass. Despite carbon fiber is stronger than glass [1]-[4], in some aerospace part as electronic devices, antennas, etc, however, material that avoid signal inference is needed. In this case, the use of glass fiber is still crucial.

Glass fibers that widely used for transportation applications are S-glass and E-glass types. S-glass is designed for application with higher mechanical properties than E-glass [5]. On the other hand, the price of S-glass is substantially more expensive than E-glass. So, combination between these two fibers may beneficial to produce desired mechanical properties, but it still considers material costs. However, the desired mechanical properties may also be influenced by fabrication techniques, resin type, and fiber architectures, due to ability resin to flow and wet the fiber and bubble that trapped in produced samples, etc.

Manuscript received July 31; revised December 12, 2020.

Onny Ujianto is with the Center for Polymer Technology, The Agency for Assessment and Application of Technology, Indonesia (e-mail: onny.ujianto@bppt.go.id).

Some previous studies reported effect of different manufacturing method, resin system as well as fiber architectures and combination on composite properties. Abdurohman and coworkers compared tensile modulus and strength as well as morphology of samples prepared by hand lay-up, vacuum infusion and vacuum bagging on E-glass EW 185/Lycal composites [6]. They found that vacuum infusion samples had better modulus and strength than those of vacuum bagging and hand lay-up. Another study also reported higher tensile modulus and strength of kenaf/polyester composites produced by vacuum infusion than hand lay-up [7]. Both studies agree that vacuum infusion samples had better tensile properties due to compression force that enable resin to spread on the fiber as well as vacuum conditions that able to reduce gases and void. Meanwhile, Sharba, *et al*., studied effect of different resin system and processing methods on mechanical properties of kenaf fiber composites [8]. Dai and colleagues explored deeper on the effect of different fiber architectures [9]. However, none of these studies observed interaction between variables.

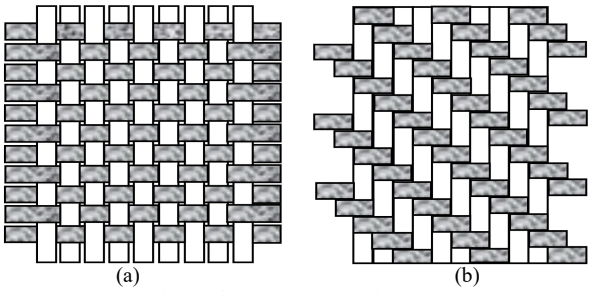
This research aimed to study glass fiber composites mechanical properties and morphology as respected to different fabrication techniques, resin system and fiber stacking. Mechanical properties of composites were focused on tensile modulus and strength as well as compression strength, while morphology were analyzed to observe fiber – resin interaction of sample with the highest and lowest tensile properties, as well as fracture surfaces of compression samples. Analysis on the effect of variables on mechanical properties was performed using general full factorial experimental design.

II. Materials and Methods

A. Materials

Epoxy resin Renlam LY 5138-2 with hardener Renlam HY 5138 from Hunstman, Germany, and Vinyl Ester resin Ripoxy R-802 EX-1 with catalyst Mepoxe and Promoter-EX from Showa Highpolymer, Singapore were used as composite matrix. Viscosity of epoxy resin was 500 – 700 mPa.s, while that of Ripoxy was 400 – 600 mPa.s at 25 °C. Glass fibers used in this research were woven roving E-glass EW-130 and S-glass SW220B-90A purchased from PT. Justus Kimiaraya, Indonesia, with architectures illustrated in Fig. 1. Density of each used fiber was represented by the number on fiber code, meaning that density of E-glass was 130 gram/m^2, while S-glass was 220 gram/m^2.

doi: 10.18178/ijmmm.2020.8.1.477



(a) (b)

Fig. 1. Fiber architectures: (a) E-glass, (b) S-glass.

B. Composite Preparation

Resin formulations were done accordingly to manufacture recommendation. Epoxy resin was mixed to hardener with ratio 100 : 23, while Ripoxy was mixed to 2 wt% of catalyst and 0.6 wt% of promoter-EX. All formulas were mixed manually 60 – 90 second in plastic pot, and applied to fabricate the samples once it was ready.

Samples were produced by varying manufacturing technique (vacuum bag or infusion), resin types, as well as fiber combinations, as shown in Table I. Vacuum assisted techniques were used to fabricate the samples as these produced less bubble than hand lay-up process [6]. All samples were fabricated by combining two fiber types (A and B), with 9 plies for each fiber. All samples were produced using flat-glass mold with fiber type A was stack on the mold surface, while B was arranged on the top of the A (Fig. 2). Illustration of sample fabrication using vacuum bag and infusion are shown in Fig. 3 and Fig. 4, respectively.

TABLE I: COMBINATION ON COMPOSITE SAMPLE FABRICATIONS

Run	Metode	Resin	A	B
1	Vacuum Bag	Epoksi	E-glass	E-glass
2	Vacuum Infusion	Epoksi	E-glass	E-glass
3	Vacuum Bag	Epoksi	S-glass	E-glass
4	Vacuum Infusion	Epoksi	S-glass	E-glass
5	Vacuum Bag	Vinyl Ester	E-glass	E-glass
6	Vacuum Infusion	Vinyl Ester	E-glass	E-glass
7	Vacuum Bag	Vinyl Ester	S-glass	E-glass
8	Vacuum Infusion	Vinyl Ester	S-glass	E-glass

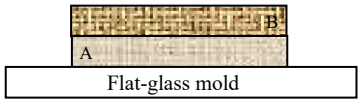
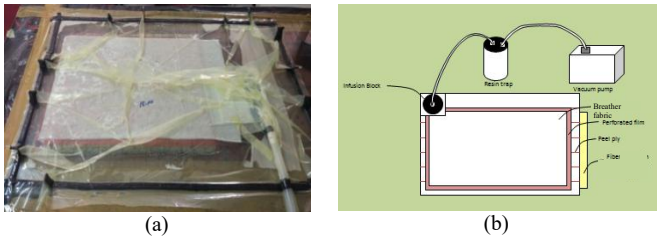
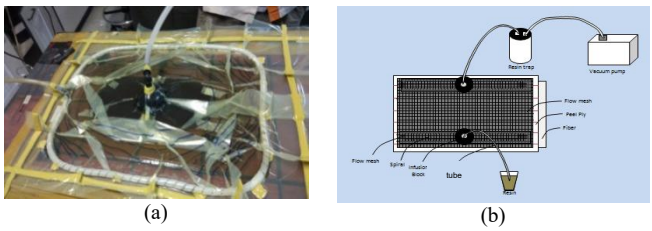


Fig. 2. Fiber stacking during sample fabrications.



(a) (b)

Fig. 3. Sample Fabrication using Vacuum Bag: (a) Manufacture process, (b) Process illustration.



(a) (b)

Fig. 4. Sample Fabrication using Vacuum Infusion: (a) Manufacture process, (b) Process illustration.

1) Vacuum bag technique

Sample fabricated by vacuum bag technique is illustrated in Fig. 3. It was done by laying up the mixed resin on the mold surface and fiber using paint brush. The arranged fibers were then covered by peel ply and followed by breather fabric. The process was then continued by covering the stacked materials with vacuum bagging film that connected by tube to resin trap and vacuum machine. Once it was started, this vacuum system sucked the resin that flowed and wet the fiber. The excess resin was then flowed to resin trap through the tube. The pressure applied on this technique was -0.8 for all samples.

2) Vacuum infusion technique

Samples fabrication using vacuum infusion technique was done by arranging fiber, peel ply, flow mesh and vacuum bag started from mold surface on the bottom to the upper layer as shown in Fig. 4. Resin was sucked and flowed to the fiber through the flow mesh. In this research, one resin inlet and one vacuum port located on side-by-side on the edge of the arranged fibers was used to ensure resin wettability to fibers.

C. Characterizations

All samples were characterized using identical test standards. Fabricated and cured samples were cut according to ASTM D3039 for tensile and ASTM D6641 for compression. All specimens were conditioned at 23 ± 2 C° and 50 ± 10 % of relative humidity.

Tensile and compression tests were conducted using Universal Testing Machine (UTM) Shimadzu AGX-plus 50 kN. Tensile test were done at 2 mm/minute of crosshead rate, with 150 mm of distance between grips. Compression test was done at 1.3 mm/minute of compression rate, with 12.7 mm of distance between grips.

Analysis on tensile as well as compression data was done according to general full factorial design using Minitab software. The model was selected by considering significance factor (p-value < 0.05) as well as the highest adjusted R-square.

Morphology analysis was done to correlate the lowest and highest value of tensile property to sample structures. The analysis was done by observing images produced using secondary electron method on JEOL JSM 6510LA at 5 kV. The analyzed images were taken from cut cross section untested samples. Meanwhile, failure analysis on samples due to compression was done by observing fracture surface produced using Hirox digital microscope, with 50x of magnification.

III. RESULTS AND DISCUSSIONS

A. Analysis on Mechanical Properties

Table II presents results of the mechanical properties samples prepared by vacuum bag as well as vacuum infusion. Tensile modulus vary from 4.5 ± 0.6 (Run 4) to 11.5 ± 0.8 (Run 6) GPa, while the strength were 229.6 ± 15.0 (Run 3) to 321.4 ± 8.5 (Run 6) MPa. 156.4 ± 16.2 (Run 8) to 287.9 ± 21.8 (Run 1) MPa. The highest value of tensile modulus, strength and compression strength were more than

double (2.6), 1.4 and 1.8 of the lowest one, respectively.

TABLE II: RESULTS OF MECHANICAL TEST COMPOSITE SAMPLES

Run	T. Modulus [GPa]	T. Strength [MPa]	Comp. Strength [MPa]
1	10.8 ± 0.5	273.4 ± 16.5	287.9 ± 21.8
2	11.2 ± 1.1	309.2 ± 3.9	284.9 ± 24.9
3	7.5 ± 0.4	229.6 ± 15.0	182.7 ± 18.2
4	4.5 ± 0.6	304.1 ± 21.2	217.7 ± 14.0
5	9.6 ± 0.4	259.3 ± 40.2	239.6 ± 12.8
6	11.5 ± 0.8	321.4 ± 8.5	244.0 ± 19.4
7	8.9 ± 0.3	275.8 ± 14.4	163.4 ± 16.6
8	11.3 ± 0.7	296.4 ± 21.5	156.4 ± 16.2
Rata2	**9.4 ± 2.4**	**283.6 ± 30.1**	**222.1 ± 51.3**

The effect of each factor on the observed mechanical properties was analyzed from analysis of variance using Minitab software, which resulted p-value shown in Table 3. The Table shown that despite all values of R^2 as well as R^2 (adjusted) were higher than 80%, only model of tensile strength and compression strength have p-value less than 0.05, suggested significant effect of one or more variable to change the strength. On the other hand, model of tensile modulus was higher than 0.05, suggested that variable applied in this research was not significantly change the modulus.

TABLE III: P-VALUE OF MECHANICAL TEST DATA

Terms	p-value		
	Tensile		Compres.
	Modulus	Strength	Strength
Model	0.297	0.038	0.013
Linier	0.271	0.027	0.008
Method	0.642	0.010	0.276
Resin	0.242	0.202	0.013
Layer. A	0.166	0.100	0.003
2-way interactions	0.249	0.175	0.222
Method * Resin	0.254	-	0.222
Method * Layer. A	-	-	-
Resin * Layer. A	0.200	0.175	-
3-way interactions	0.409	0.055	0.129
Meth. * Res. * Lay. A	0.409	0.055	0.129
R-sq	97.4%	98.5%	99.5%
R-sq (adjusted)	81.9%	94.7%	98.2%

Variables significantly influenced tensile strength on 95% of confidence level was fabrication method (p-value = 0.010), while those of compression strength were resin type (p-value = 0.013) and fiber type applied as layer A (p-value = 0.003). Moreover, if the confidence level was decreased to 90%, the interaction of all variables (fabrication technique, resin type, as well as fiber on layer A) also significantly influenced tensile strength.

Further analysis on the effect of variables on mechanical properties was done by observing main effect plot of tensile strength (Fig. 5(a)) as well as compression strength (Fig. 5(b)), respectively. The tensile modulus as well as interaction between variables would not be analyzed further as it was not significantly influenced the properties.

Fig. 5 presents main effect plot of variables on tensile strength. It is shown that overall, tensile strength increase significantly from about 26 to 31 MPa by changing manufacturing technique from vacuum bag to vacuum infusion. This result is similar to previous reported study [6]. The higher tensile strength samples produced using vacuum infusion might be influenced by the higher fiber content and less bubbles compare to that of manufactured using vacuum bag.

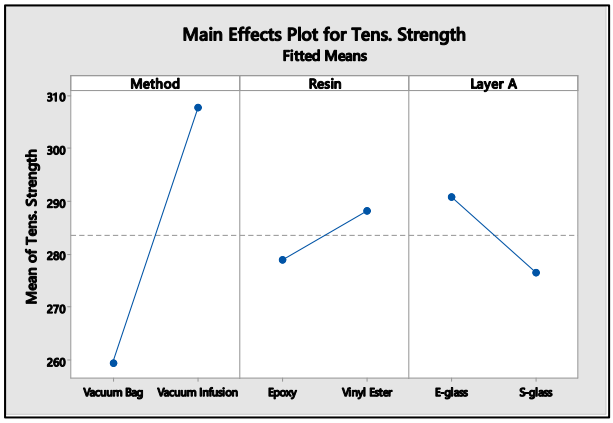


Fig. 5. Main effect plot of tensile strength.

High fiber content and less bubbles highly related to the easiness of resin to flow (viscosity) and density of fiber on layer A, namely S-glass or E-glass. In vacuum infusion, the resin was transferred from the top (E-glass) to bottom layer (S-glass or E-glass). The higher of fiber density used on layer A and B, the more difficult the resin for wetting all the fibers. As the top layer always used E-glass which less density than S-glass, the wettability of resin on this layer for infusion process would be better than vacuum bag thus improve adhesion between resin and fiber. The resin then continuously penetrated the bottom layer from the top. The resin flow through the top layer was also facilitating the excess resin move to resin trap. As a result, the samples were produced with higher fiber content. On the other hand, in vacuum bag process, most resin started to flow from the bottom layer. Due to the density of S-glass, some resin might difficult to penetrate the fiber, resulted samples with higher resin content than that of processed by infusion. These also explained to decrease of the tensile strength by changing fiber type from E-glass to S-glass. However, the wettability might be improved by applying low viscosity resin. This also explained why the tensile strengths of samples prepared from Ripoxy (viscosity : 400 – 600 mPa.s at 25 °C) were higher than that of Epoxy (viscosity : 500 – 700 mPa.s at 25 °C).

Another possible caused the higher tensile strength on samples produced by infusion process than vacuum bag was less bubble or air trap on the composite structures. In infusion, firstly, the vacuum sucked the air on the system before the resin, resulted less bubbles. In contrast, vacuum bag process needed preliminary process as laying-up the fiber with the resin manually before the vacuum started to suck the air and excess resin. This condition might facilitate good wettability on the fibers, however the resin experienced difficulty to flow and penetrate the high density fiber as S-glass. It also depended on worker's skill and

experience [6]. These tricky conditions might cause the bubbles or air traps which difficult to be reduced as the system did not facilitate the excess resin and bubble to move easily.

Meanwhile, the lower tensile strength on samples prepared using S-glass than E-glass might also be due to fiber architectures as shown in Fig. 1. The compact fiber on E-glass promotes less crimp to hold applied load during tensile test. The more compact structure on E-glass also ensures less variation during weaving process. On the contrary, less compact structure on S-glass might cause fiber damage during process [9]. As a result, tensile strength samples prepared using E-glass was higher than those of S-glass due to more compact architecture.

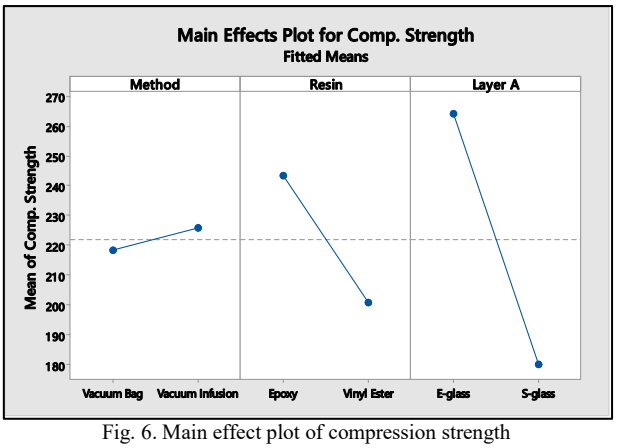


Fig. 6. Main effect plot of compression strength

Meanwhile, Fig. 6 shows the main effect plot of compression strength. As shown in Table III and Fig. 6, effect of fabrication technique did not significantly change compression strength. In contrast, Fig. 6 shows that vinyl ester and S-glass significantly reduced compression strength as suggested on Table III compare to epoxy and E-glass. The lower compression strength samples produced from vinyl ester than epoxy might be attributed to initial resin property. While, the imbalance transfer load on samples with S-glass – E-glass fiber combination as well as fiber density that inhibit resin to penetrate the fiber causing resin rich sample might lead to lower compression strength than those prepared with E-glass – E-glass structures.

B. Analysis on Sample Morphology

Morphology analysis was done to observe sample Run 3 and 6 for contrasting the lowest and highest tensile strength. This samples were chosen rather than Run 4 and 6 as the lowest and highest tensile modulus due significant effect shown and explained on previous section.

The morphology of sample Run 3 and 6 are presented on Fig. 7. The figure shown that most area of sample Run 3 (Fig. 7(a)) were covered by resin represented by smoother surface suggested resin rich sample. In contrast, Fig. 7(b) depicts fiber structure cover with less resin. This also shown in bigger magnification (200x). This might happen as sample Run 3 was produced by vacuum bag which has more resin on product than infusion, and higher viscosity resin (epoxy) that difficult to penetrate compact and dense structure of S-glass. The result of this resin rich sample was lower tensile strength than that of Run 6 produced by infusion using vinyl ester resin and E-glass on layer A.

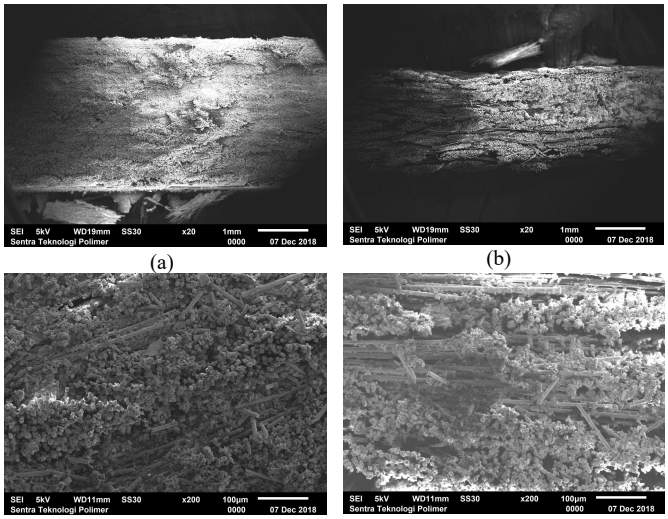
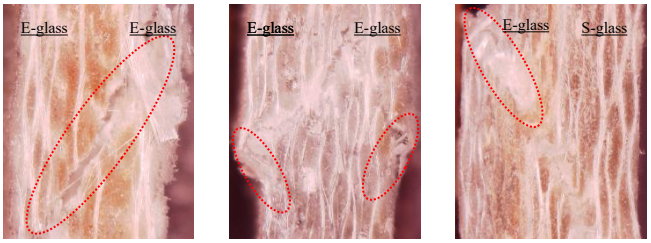
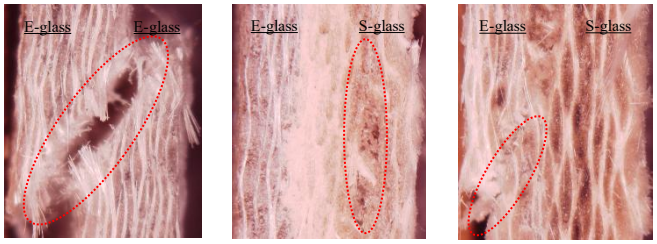


Fig. 7. SEM pictures of composite samples at various magnifications: (a) Run 3, 20x, (b) Run 6, 20x, (c) Run 3, 200x; (d) Run 6, 200x;



287.9 ± 21.8 MPa (a) 284.9 ± 24.9 MPa (b) 182.7 ± 18.2 MPa (c)

Fig. 8. Fracture surfaces samples after compression test prepared from Epoxy: (a) V. Bag – E-glass (Run 1), (b) Infusion – E-glass (Run 2), (c) V. Bag – S-glass (Run 3).



244.0 ± 19.4 MPa (a) 163.4 ± 16.6 MPa (b) 156.4 ± 16.2 MPa (c)

Fig. 9. Fracture surfaces samples after compression test prepared from Vinyl Ester: (a) Infusion – E-glass (Run 6), (b) V. Bag – S-glass (Run 7), (c) Infusion – S-glass (Run 8).

Fracture surface samples after compression are presented in Fig. 8 and Fig. 9. Fig. 8 compares some samples related to sample with the highest compression strength (V. Bag – Epoxy – E-glass), while Fig. 9 compares those related to the lowest value (Infusion – Vinyl Ester – S-glass). From the Figures, it is shown that most samples failed due to shear, kinking, and breakage of resin leaded to delamination.

On Fig. 8 and Fig. 9, it is shown that samples produced from E-glass had shear (Fig. 8(a) and Fig. 9(a)) and kink (Fig. 8(b)) failure suggested good transfer load due to proper lamination between layer A and B. On the other hand, resin crack surface Fig. 9(b) and Fig. 9(c)) and un-complete shear failure (Fig. 8(c)) on sample with S-glass on layer A might be attributed to low imbalance transfer load between layer with E-glass and S-glass. This might also influenced by worse lamination among S-glass due to resin difficulty to

penetrate compact and dense S-glass compare to E-glass, as explained on SEM section.

IV. Conclusions

Comparison of manufacturing technique, resin type and fiber combination on glass fiber composites was done with respect to mechanical properties and morphology analysis. The results showed no significant effect of variables on tensile modulus. However, sample fabrication was significantly influence tensile strength, while resin type and fiber used on layer A significantly contributed to compression strength. It was shown that vacuum infusion had better tensile strength than vacuum bag due to less resin and bubble. On compression strength, epoxy samples showed higher value than those of vinyl ester suggested better initial resin property due to higher viscosity. While, lower compression strength samples with S-glass applied to layer A than E-glass might be caused by the imbalance transfer load as well as fiber density inhibiting resin penetration and causing resin rich samples. Most samples failed on compression test due to shear, kink and resin break.

Conflict of Interest

The authors declare no conflict of interest regarding to this publication.

Author Contributions

First author contributed to paper arrangement, mechanical, statistical and fracture surface data collection as well as analysis. Second author contributed to material selection and mechanical data collection and analysis. Third author contributed to SEM data collection and analysis. Fourth author contributed to final result analysis.

Acknowledgment

Authors would like to thank you to Center for Polymer Technology, Agency for Assessment and Application of Technology (BTP – BPPT) and Aeronautics Technology Center, National Institute of Aeronautics and Space (Pustekbang - LAPAN) Indonesia for financial supports. Best gratitude was also given to Mr. Singgih, Yogi, Hakim, and Ms. Ara for helping in sample manufacturing and testing.

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Onny Ujianto is a research engineer in the Center for Polymer Technology, BPPT, Kawasan Puspiptek, Setu, South Tangerang, Indonesia. He was born in Purwokerto, Indonesia on July 11, 1982. He obtained his master degree from RMIT University, Melbourne, Australia in 2015. His research interests are polymer processing, as well as structure – property relationships of polymer composites.

Afid Nugroho is a research engineer in Aeronautic Technology Center LAPAN, Kawasan Perkantoran Pustekbang LAPAN, Sukamulya, Rumpin, Bogor, Jawa Barat, Indonesia. He was born in Klaten, Indonesia on January 24, 1983. He obtained his master degree from Gadjah Mada University (UGM) in 2017. His interests are composites structure, nano materials and natural fibers composites for aircraft or Unmanned Aerial Vehicle (UAV) structure.

Hendro Sat Setijotomo is a senior research engineer in the Center for Polymer Technology, BPPT, Kawasan Puspiptek, Setu, South Tangerang, Indonesia. He was born in Kediri, East Java, Indonesia. He obtained his master degree from University of Indonesia in 2010. His research interest are composite technology, polymer processing and product development.

Atik Bintoro is a senior researcher in Aeronautic Technology Center LAPAN, Kawasan Perkantoran Pustekbang LAPAN, Sukamulya, Rumpin, Bogor, Jawa Barat, Indonesia. He obtained his master degree from University of Indonesia (UI) in 2002. His interest is composites structure for aircraft or Unmanned Aerial Vehicle (UAV) structures.