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FIBER-REINFORCED POLYMER COMPOSITE FOR USE OF A BLADE RUNNER'S ARTIFICIAL LEG OF LOWER-LIMB AMPUTEES

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ABSTRACT

Carbon fiber sports prostheses have been commonly implemented for lower-limb amputees to participate in competitive sports in which a blade runner's artificial legs are embedded into the structural design of artificial limbs. In the present study, the blade runner's artificial legs of the fiber-reinforced polymer composite with the good impact of spring load resistance were fabricated. The composite was prepared using the prepreg carbon fiber and made through the curing method out of autoclave with the manufacturer's recommended cure cycle (MRCC) profile. The fabricated composites with a variation of the number of layers were then subjected to mechanical property and density in addition to voids evaluation. Results showed that the artificial leg composites with layers of from 25 to 40 could endure under compressive loading in the range of 1442 N-2266 N for each step. Therefore the composite can be implemented for the lower-limb prostheses with the user's body weight less than 70 kg. The outcome of the study may also add knowledge for fabricating the blade runner's artificial legs at a low cost.

Keywords: blade runner's artificial legs, prepreg carbon fibre, out of autoclave curing method, mechanical and physical testing.

1. INTRODUCTION

Legs in the human body with two lower members function to support and move in performing daily activities. In some cases, there is an absence or deficiency of the legs, which may be caused by amputation and/or congenital deficiency making their limited activities [1]. It was reported that a high number of lower-leg amputees could be found in developing countries as Indonesia. For this reason, the need for a prosthetic device with a low-cost material is crucial for people to improve the healthy life [2].

Particularly, modern prosthetics are typically custom-made products to meet the height, weight, and muscular structure of amputees [3]. Correspondingly, foot prostheses are designed for not only walking but also used for sports activities such as running. Conversely, prostheses with the desired shape are difficult to form using a traditional manufacturing process including machining. Accordingly, the raw material selected for prostheses must be suitable for molding manufacturing technology. The use of fiber composites for prostheses provides the greatest advantage in the manufacturing stage of deep components with thin walls and compound curves [4]. In this way, using split dies along with the resin transfer molding for preparing composite methods makes it possible to yield any kind of complex structures [5].

Additionally, the carbon fiber-reinforced polymer (CFRP) composites can be made for the structural design of artificial limbs of the amputee to be able to participate in competitive sport [3]. In the 2018 Asian Para Games, a female athlete could run for short distances of 100 meters with a special artificial leg. However, the only limited runner prosthesis could be found in the market, whereas the runner prosthesis as a customized product is sold at a relatively high cost.

Further, the customized product of foot prostheses has been fabricated with a diverse range of models according to the needs of amputees [3] [6]. Correspondingly, several blade runners' artificial leg prostheses using a combination of stainless steel, aluminum, titanium, fiber, and polyethylene have been manufactured. In particular, sports prostheses with the designed carbon fiber provided lower-limb amputees who can dynamically take part in competitive sports. In some cases, the customized designs of the runner prosthesis may require adjustments to microstructures of composite materials such as laminate lay-up, fiber orientation, and/or laminate thickness [7]. Specifically, biomechanical and reusability aspects are important factors considered in the design of prostheses for runner's feet [8]. Consequently, significant efforts on advanced research on polymer composite materials have been made leading to technical improvements toward broad applications for modern orthopaedic medicine and prosthetic devices

Now, each device has been designed to provide a quality product with the 3C-level (control, comfort, and cosmetics) with slightly different properties [3].

Recently, intensive research has been focused on a low-cost-artificial leg with CFRP composite. The low-cost- artificial leg has been initially designed for general applications, and later has been improved incredibly with quality levels of prostheses for sporting and recreational function [10] [11]. In particular, CFRP composites have a superior strength to weight ratio compared to monolithic materials and provide outstanding biocompatibility. Therefore, many prosthetic feet with CFRP composites could be found on the market for individuals with transtibial amputation on the subject of most specialized designs of sports prostheses in running and jumping events.

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Although the experimental and computational study of lower limb prosthetics has been reported in several publications [1] [2] [11] [12] [13], there are still many aspects that require more research works on the less expensive devices with comfort, good mechanical performance, and manufacturing reliability [14].

In the present study, a prototype of the blade runner's artificial leg prosthesis with the good spring effect was made with a fiber-reinforced composite. The fiber composite reinforcement was considered superior to endure compressive loads as a result of the spring effect. The research work was focused on evaluating the mechanical and physical properties of blade runner's artificial legs below the knee made of the prepreg carbon fiber. This result of the study was expected to add knowledge on developing the high-quality domestic products of the blade runner's artificial legs.

2. MATERIALS AND METHOD

2.1 Raw Material Used in the Study

A prepreg (pre-impregnated) carbon fiber material (RGC200FR-43) was considered in the study to be the right material for manufacturing the artificial legs for runners. The prepreg carbon fiber was purchased from Qingdao Regal New Material Co., Ltd, China, having characteristics of twill 3x3-200 GSM and thickness of 0.25 mm. This material was obtained as a semi-finished composite product consisting of a high viscosity matrix and a continuous reinforcing fiber. The characteristics of pre-preg carbon fiber are presented in Table-2.1. The prepreg was then cut into the dimension 55 cm x 7 cm for one layer. The number of layers (25, 30, and 40) were prepared for the prosthetic runner's leg below the knee. Before fabricating the prepreg composite, the fiber was initially moistened with a matrix material yielding a pre-impregnated semi-finished product.

Table-2.1. Prepreg carbon fiber specification.

Prepreg Material	Carbon Fiber Pre-preg
Type of prepreg	Epoxy Resin + Carbon Cloth
Curing temperature	Low temperature (70 °C) and Post curing (120 °C)
Curing time	120 - 180 min
Storage life at -5 °C	6 Months
Storage life at -18 °C	12 Months
Resin content	20% - 45%
Width (mm)	1000
Thickness (mm)	0,25
Fabric density (gsm)	200

2.2 Preparation of CFRP Composites

The Out-of-Autoclave (OOA) curing method was implemented to prepare the CFRP composite because the curing process did not require a pressurized oven and relatively low cost. The curing profile was selected according to the Manufacture's Recommended Curing Cycle (MRCC), as shown in Figure-2.1. This curing profile was obtained from the prepreg carbon fiber provider based on the WP-R5600W3K technical datasheet.

Figure-2.1. Curing cycle of MRCC.

The curing cycle of preparing composite starts at room temperature of about 25 °C. Subsequently, the temperature increases to 70 °C at a ramp rate of 1 °C/min and dwells for 4 hours. Then the temperature increases again to 120 °C at a ramp rate of 2 °C/min and dwells for 1 hour. Finally, the cooling down of the composite proceeds by annealing to room temperature. The detailed curing profile is presented in Table-2.2.

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Table-2.2. Curing profile step of MRCC.

Step	Start Temp	Ramp Rate	Duration	End Temp	Elapsed time
1	~ 25°C	1°C /min	00:50	70°C	00:50
2	70°C	Dwell	04:00	70°C	04:50
3	70°C	2°C /min	00:25	120°C	05:15
4	120°C	Dwell	01:00	120°C	06:15
5	120°C	Annealing	--	~ 25°C	07:15

2.3 Geometry of the Blade Runner's Artificial Leg Sample

The geometry of the designed blade runner's artificial legs was tested in the study, according to the model of the Sprinter's King (Roadrunner) that has the smallest maximum stress and the largest safety factor value compared to the geometry of the design of other under-knee prosthetic runner's legs. The designed geometry of the blade runner's artificial leg is shown in Figure-2.2. Moreover, each layer of pre-preg carbon fiber for the blade runner's artificial leg has a dimension of 55 cm x 7 cm for each layer. The thickness of the geometric design was varied according to the number of layers (25, 30, and 40 layers).

Figure-2.2. Designed geometry of the blade runner's artificial leg with Sprinter's King [15].

2.4 Physical and Mechanical Testing of the Composite Samples

Physical tests were performed on the samples, including density and defect (voids) evaluations. Voids feature was observed with 10 times magnification microscope on 3 geometry sample points as shown in Figure-2.3. The density of each sample was determined by the Archimedes method. Moreover, the mechanical test of each sample was conducted by a compression test on a universal testing machine.

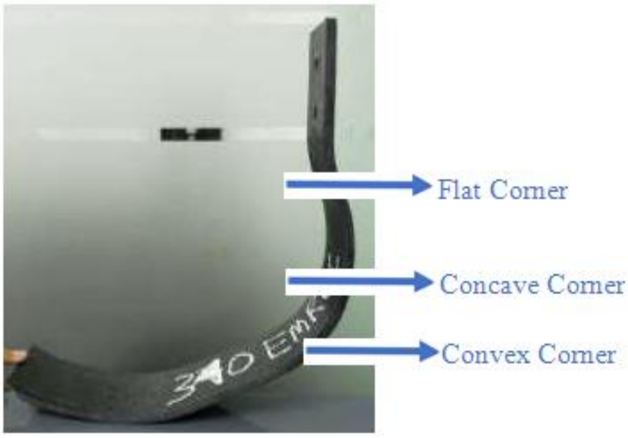

Figure-2.3. Geometry corner of the defect test points.

2.5 Analysis of Variance

Results of compression testing from each blade's runner legs with varying layers present the highest maximum compressive strength after the failure. In this work, three specimens having a specific layer subjected to compressive testing were considered. The mean and standard deviations of values of the compressive strength were then presented. It is regarded here that a statistical test was performed for quantitative variables of compressive strength. Accordingly, the mean was computed to present the interval and ratio levels of measurement.

Furthermore, the void observation was performed to examine defect present at each geometry sample point of the blade runner's legs. Three specimens having specific layers were also subjected to density test. The mean and standard deviation of density value was presented to compare with the reported density of the commercial blade runner's legs.

3. RESULTS AND DISCUSSIONS

3.1 Maximum Breaking Load of Blade Runner's Artificial Legs

A compression test was performed on the prototype of the blade runner's artificial legs to examine the maximum breaking load that can be sustained on the sample. Results of the tested blade runner's artificial legs with 25, 30, and 40 layers are presented in Table-3.1. In general, composites showed some fluctuations in the mean maximum breaking load that may relate to thickness variations in the samples. Also, values of the mean

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breaking load for all samples have a low standard deviation.

It shows that the blade runner's artificial leg having 40 layers was broken at a maximum breaking load of 5052.85 N. Evidently, fewer layers of the blade provided the less breaking load can be suffered by the blade. Conversely, the Sprinter's King prosthetic runner's legs can endure at the breaking load of 7000 N

[15]. Here the prosthetic runner leg below the knee can suffer under a breaking load of 3360 N. When the leg tested in a cycle at a load of 3000 N provided the test of 300 000 cycles. The result can be estimated that the foot prosthetic can be used for one year with 3 hours of use per day and after that, the prosthetic must be replaced. The standard leg cycle testing, commonly used in the prosthetic runner, is 1330 N for 2 000 000 cycles [16]. Based on the standard breaking load of

Sprinter's King (Roadrunner) prosthetic runner's legs, each variation of blade runner's artificial legs examined in this study has met the standard of breaking strength value.

It was reported that the load can be received by prosthetic runner legs below the knee equivalence with 2.1 to 3.3 times the user's body weight [17]. For individuals having a weight of 70 Kg, the prosthetic runner's legs will be subjected to the load in the range of 1442 N - 2266 N. Therefore, all blade runners' artificial legs examined in the study have met the requirement of the maximum load that can be suffered by the prosthetic runner's leg for a user's body weight of 70 Kg.

Table-3.1. Values of breaking load of the blade samples with variation of layer.

No.	Layer	Thickness (mm)	Mean maximum breaking load (N)
1	25	6.8	3473.382 (56)*
2	30	8.7	4575.828 (70)
3	40	10.14	5052.854 (65)

*Number in parenthesis represent standard deviation of the mean values

3.2 Density of Blade Runner's Artificial Legs

Density measurement was carried out to obtain the density value for each variation of the carbon fiber layer that makes up the blade runner's artificial runner's legs. Measurement was done by weighing each variation in the number of layers of the blade runner's artificial legs using digital scales to get the mass of the runner's prototype. After getting the mass, calculations of density are performed using the Archimedes method (density: mass/volume) (Table-3.2). It can be seen that the blade runner's leg with a variation of 25 layers has a density value of 1.22 g/cm3, 1.23 g/cm3 for 30 layers, and 1.41 g/cm3 for 40 layers, respectively. The density value itself determines whether the composite is lighter or not, because of directly proportional to the mass of the specimen. It was recommended that the blade runner's artificial leg has a light mass in order to make it easier for the user to run. The lighter the blade mass, the lighter the load the user feels when running.

Table-3.2. Density of the composites with varying carbon fiber layers.

No.	Layer	Volume (cm^3)	Mass (g)	Density (g/cm^3)
1	25	261.8	318.36	1.22
2	30	334.95	411.90	1.23
3	40	390.39	550.36	1.41

3.3 Defect Evaluation of the Blade Runner's Artificial Leg

The defect examination aims to examine the voids generated after fabricating the blade runner's artificial leg. The void images of the artificial blade runner's leg were observed at 3 points; flat corner, concave corner, and convex corner (Figure-3.2). Apparently, the void images were obtained at 3 different points showing the void in each geometry. In the sample of flat corner geometry points, there are several void images relating to the shrinkage during hardening. However, there are not many void images found in the convex corner geometry, and the flat void angle, because the convex corner on the geometry of the runner's leg has a large radius. It looks at different images on the sample at the concave corner geometry which has clearly visible voids and thickening. This is because the concave corner in the blade runner's artificial leg geometry has a small radius with complex geometry.

Further, defects generated during manufacturing can worsen with increasing size and geometric complexity, which is mainly the thickness variation at the difference in thickness between the corner and the plane of the geometry

The main reason for thickness variations in composites with complex structures relates to the difference in pressure between the corners and the square corners. Additionally, the formation of voids may have resulted from the out-of-autoclave process.

The use of the autoclave and out-of-autoclave processes for forming composites indicates that the autoclave process may produce composites with very minimal voids compared to the out-of-autoclave process even at very high humidity [19] [20]. In contrast, the out-of-autoclave process is more sensitive to air and humidity, thereby causing a higher void of the product. Additionally, the voids may be formed because air is trapped in the layer during the coating, pre-purging, and other processes such as bagging which is not tight thereby being leakage and resin evaporated during the process [21].

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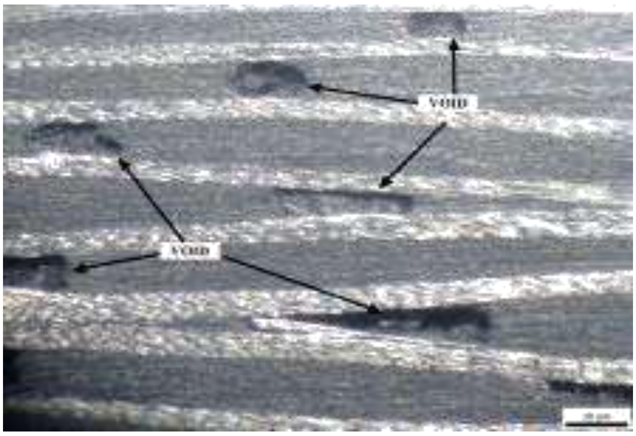
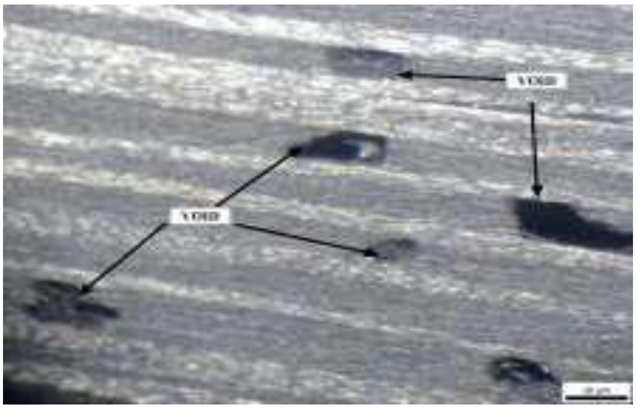


(a)



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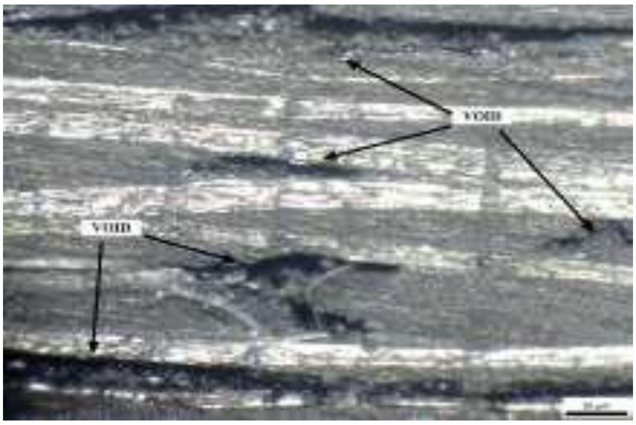
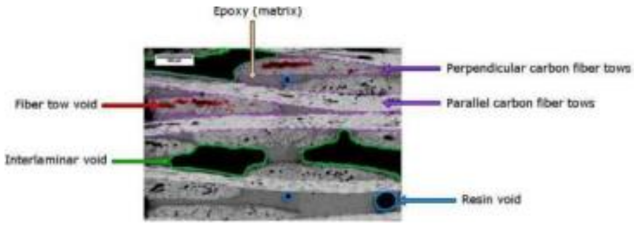


(c)

Figure-3.2. Defects of the blade examined at enlargement of 10x for the point geometry sample; (a) flat corner, (b) convex corner, and (c) concave corner.

The microstructure of the pre-preg carbon fiber on the artificial blade can also be examined on layers of carbon fiber, epoxy (matrix), and voids. Here the structure of the pre-preg carbon fiber layer is obvious (Figure-3.3a), while the pre-preg carbon fiber constituent layer is also evident in Figure-3.3b. This result is a similar result, previously reported in the literature [22] [23] [24].



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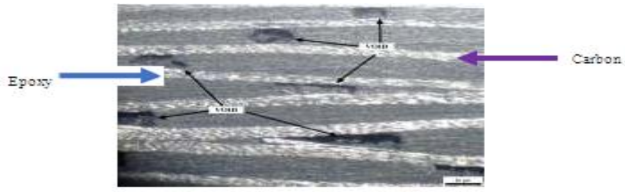

(b)

Figure-3.3. (a) Cross-section of an un-debulked and uncured prepreg laminate, showing different types of voids and (b) constituent layers of pre-preg carbon fiber blade runner's artificial leg.

CONCLUSIONS

The study has demonstrated successfully the manufacturing of the blade runner's artificial leg using the out-of-autoclave prepreg carbon fiber according to the manufacturer's recommended curing cycle. The blade runner's artificial legs with a variety of 25, 30, and 40 layers have met the requirement for use of an amputee runner with a bodyweight of 70 kg. The blade runner's artificial leg fabricated with the out-of-autoclave method provided the product with the minimum number of voids (macro defect). The results of the density test show the blade runner's artificial leg with a high layer of 40 layers has a density value of 1.41 g/cm^3. In view of the service life, the blade runner's artificial leg with a variation of 40 layers is recommended.

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Conflict of interests

The authors declare no conflict of interests.

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