Manufacture of Carbon Fibre-Based Energy Storage and Return (ESAR) Foot Prosthesis Using Vacuum Bagging Curing Method

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Abstract. Currently, in Indonesia, lower limb amputees were utilizing a static cosmetic foot prosthesis which is not efficient. The development of a cutting-edge foot prosthesis which can store energy is need to be conducted. The Energy Storage and Return (ESAR) foot prosthesis is designed to store energy during the initial stance phase (heel strike) and release it as propulsive energy in the later stance phase, enhancing walking efficiency. In this study, carbon fibre material is used to produce ESAR foot prosthesis using vacuum bagging curing method. The finished product was analysed using cross-sectional micrography and tested with ISO 10238:2016 compression testing standards. The micrography analysis shows a small imperfection in the form of void and delamination. The compression test resulting in respectable capability of the carbon fibre ESAR foot prosthesis to store and releasing the energy when used for walking. This product is expected to be an upgrade for the amputees, and minimizing the import of the related product for Indonesia.

Keywords: Amputee, Carbon Fibre, Curing, Energy, Foot Prosthesis, Tensile.

1. Introduction

The loss of limb function, particularly in the lower extremities, often hinders individuals from engaging in activities such as walking [1] and other daily tasks. Currently, active prosthetics with internal force sources are still in the development stage, while passive

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prosthetics continue to dominate the market [2]. Prosthetics are expected to replicate the lost limb's function to the fullest extent possible. Typically, amputees use prosthetic legs with a Solid Ankle Cushioned Heels (SACH Foot) design, which primarily serves to reduce impact but stores and releases minimal elastic energy [3]. The SACH Foot falls under the category of conventional foot prostheses, lacking movements like plantar flexion and dorsiflexion. Consequently, prostheses with the SACH Foot design are limited in mimicking the kinematics and kinetics of the gait cycle, only reducing impact [4].

The Energy Storage and Return (ESAR) foot prosthesis is a design capable of storing energy during the loading phase at the early stance phase (heel strike) and releasing it as propulsive energy during the late stance phase, which is utilized while walking [5]. Currently, ESAR foot prosthetics are assumed to minimize metabolic energy expenditure during the walking phase in amputees [6]. Additionally, the energy storage and return design are claimed to enhance walking performance [7].

Composite materials like carbon fiber with an epoxy resin matrix are ideal for orthopedic applications such as foot prostheses due to their lightweight and durable properties [8]. Prostheses made from carbon fibre are advantageous due to their lightweight, minimizing the metabolic energy expenditure for an amputee when in use [9]. A key characteristic of composite prosthetics is that the material can be customized according to the height, weight, and muscle structure of each individual.

The ESAR foot prosthesis can be a priority choice due to its high functionality. However, existing ESAR foot prosthetics in the market are imported products with very high prices. The fact that health products are still predominantly imported is noted in research [10], stating that more than 90% of health devices used in Indonesia are dominated by foreign products. This statement aligns with the latest Indonesia's statistics data, mentioning that the import of artificial limbs, including foot prostheses, reached 74,134 US Dollars or equivalent to Rp 1,067,826,136 (more than 1 billion rupiahs). As of the proposal of this research, the researchers have not found any domestic commercial foot prosthesis products with the Energy Storage and Return (ESAR) design. From these backgrounds, the authors conduct the research according locally manufactured ESAR foot prostheses made from carbon fibre vacuum bagging curing method [11]. The morphological and compression test were evaluated to discover the quality and capability of the prosthesis.

2. Materials And Methods

The initial stage began by cutting 28 pieces of carbon fibres sheets with dimensions of 25 cm x 6.5 cm and 20 pieces of 20 cm x 6.5 cm. The specific foot molds were used for producing the two distinct carbon fibre plates. The mold is coated with PVA using a brush on the surface and air dried for 30 minutes. The fabrication process utilizing the vacuum bagging method. The critical step of vacuum bagging method is bagging and vacuuming process that can be seen in Figure 1 below. The bagging must be tight and not allowing even a small cavity to prevent the leaking and uneven vacuuming process. The vacuuming is important to make sure the resin was completely penetrating each layer of carbon fibre and dispose the excess resin. Subsequently, morphological analysis was performed using an optical microscope to analyse the defect imperfections in the finished product.

The finished foot prosthesis was subjected to mechanical testing, specifically compression tests, with loading corresponding to the gait cycle phases (heel strike and toe-off), following the selected ISO 10238:2016 testing standards [12]. The compression test is conducted to obtain the mechanical properties of the carbon fibre [13] and the deformation or displacement that occurs in the foot prosthesis when subjected to a specific load according to the loading position setting. The testing is performed using a Universal Testing Machine (UTM) in the Material Laboratory of Muhammadiyah University Semarang. The compression test procedure can be seen in Figure 2.

(a) (b) (c)

Fig 1. Critical process of vaccum bagging method: bagging process (a and b) and vacuuming (c).

(a) (b)

Fig 2. Compression test procedure for heel strike (a) and toe off (b) condition.

3. Results and Discussions

During the vacuum bagging process, the overall time utilized is between 7 to 8 hours, with the breakdown including 1 hour for preparation, 2 hours dedicated to the hand lay-up stage, 1 hour for vacuum processing, and a curing phase lasting 3-4 hours, until it can be detached from the mold. The finishing process involves sanding, and drilling holes to place bolts. Subsequently, the assembly of each part is carried out, comprising three main parts: bolts, foot adaptor, and an outsole. The foot adaptor serves as a connection between the foot prosthesis and the tube prosthesis that will be assembled with the socket. The outsole functions as an anti-slip component. It serves as an alternative foot cover. The finished product can be seen in Figure 3. The manufactured geometry aligns with the design drawing, with a deviation of less than 1%. The thickness of the ESAR foot on the top part is 7 mm, which is in accordance with the drawing. However, for the ESAR foot carbon fibre on the bottom part, it measures 6 mm, exceeding the drawing by 1 mm.

From morphological observation, the ESAR foot with inter-layer carbon fibres integrates seamlessly. No fibre pull-out is observed at the edges. However there is a small amount of void and delamination which can be assumed that the future process must be involving a more even vacuuming process [14]. The optical observation result can be seen in Figure 4 below.

Fig 3. The finished ESAR foot prosthesis.

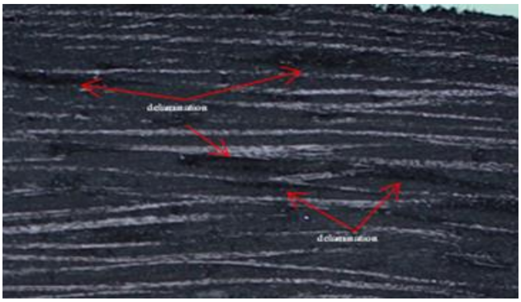

Fig 4. Results of cross-sectional optical microscope observations showing a small imperfection.

The compression testing setup involves a compression test at a 15° angle for the heel strike position and a 20° angle for the toe-off position. The operator attached an additional tool which can be adjusted for its angle. The Universal Testing Machine then applied loads ranging from 0 N to a maximum of 824 N, controlled through a computer system. At the maximum load of 824 N, the load was sustained for 30 ± 3 seconds.

Observations was conducted during the load reduction process and at maximum load. According to ISO 10328:2016 standards, a prosthesis is deemed compliant if there is no fracture during the maximum load retention. In this study, the foot prosthesis did not experience any fractures when subjected to the maximum load and held for 30 ± 3 seconds. Therefore, it can be concluded that the ESAR foot prosthesis made from carbon fibre meets the ISO 10328:2016 standards at the P4 level. The displacement value for heel strike and toe off were 18.07 mm and 16.70 mm respectively. The load-displacement graph of the test can be seen in Figure 5.

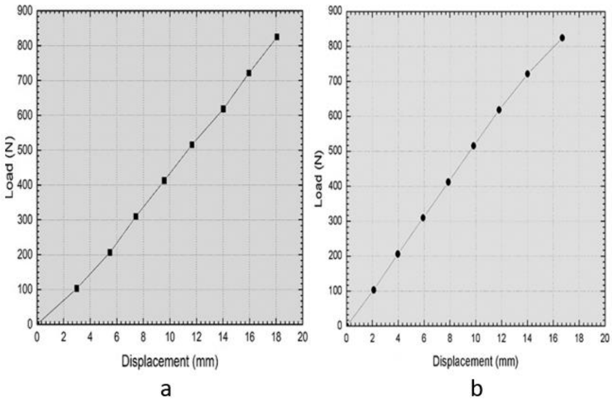

Fig 5. Compression test result heel strike (a) and toe off (b).

The advantage of the ESAR foot prosthesis in the study is the capability to store energy. In the context of prosthetics, energy can be quantified using the formula for work (W). In physics, particularly in mechanics, work is defined as the force applied to an object causing it to undergo displacement. The concept of work is inherently linked to the concept of energy. Mathematically, work is expressed as the product of force and displacement and is formulated as Equation (1) below:

$$W = (F \cos \theta) d \tag{1}$$

where:

W = work or energy (Joule)

F = maximum load (N)

θ = compression test angle (15˚ and 20˚ for heel strike and toe off respectively)

d = displacement value from compression test (m)

Using Equation (1) [15] and the compression test result, the energy calculation for the carbon fibre foot prosthesis yields the following results in Figure 6.

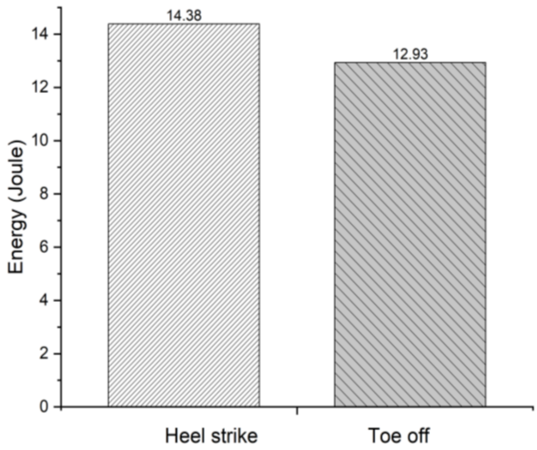

Fig 6. Energy storage values of the foot prosthesis

According to the calculations, the energy values for the carbon fibre foot prosthesis stores 14.38 J during heel strike and 12.93 J during toe-off. In this study, it is assumed that the stored energy during heel strike is equivalent to the energy released as propulsive energy (after heel strike), following the principle in physics that the received energy equals the expended energy.

4. Conclusions

The study has succeeded to produce an ESAR foot prosthesis using carbon fibre by vacuum bagging curing method. The finished product has a compliance with the design drawing but there is a small imperfection in the carbon fibre layer which can be improved by using adequate vacuuming process. The results of ISO 10328:2016 standards compression test showed displacements of 18.07 mm at heel strike and 16.70 mm at toe-off. Energy calculations for the carbon fibre ESAR foot prosthesis indicated 14.38 J at heel strike and

12.93 J at toe-off. This cutting-edge product and innovation hopefully can minimize the import of foreign active foot prosthesis especially in Indonesia.

Authors' Contributions

Alfiana Fitri Istiqomah: Conceptualization, Methodology, Manufacture and Production, Investigation, Validation, Visualization, Formal Analysis, Writing – original draft, Writing – review and editing. Rifky Ismail: Conceptualization, Methodology, Manufacture and Production, Investigation, Validation, Visualization, Formal Analysis, Writing – review and editing. Sulistyo: Conceptualization, Methodology, Manufacture and Production, Investigation, Validation, Visualization, Formal Analysis, Writing – review and editing. Deni Fajar Fitriyana: Conceptualization, Methodology, Manufacture and Production, Investigation, Validation, Visualization, Formal Analysis, Writing – review and editing. Dwi Setyawan: Conceptualization, Methodology, Manufacture and Production, Investigation, Validation, Visualization, Formal Analysis. Hartanto Prawibowo: Methodology, Manufacture and Production, Validation. Akmal Putra Fardinansyah: Conceptualization, Methodology, Manufacture and Production, Investigation. Murti Ayu Nur Safitri: Conceptualization, Methodology, Manufacture and Production, Investigation, Validation, Visualization. Jayatin: Conceptualization, Writing – review and editing, Supervision. Rilo Berdin Taqriban: Investigation, Formal Analysis, Wrting – original draft, Writing – review and editing.

Conflicts of Interest

The authors declare they have no conflicts of interest.

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