INVESTIGATION OF WOVEN COMMINGLED THERMOPLASTIC COMPOSITE FOR THE PROSTHETIC APPLICATION

Yogeshvaran.R. Nagarajan, Farukh Farukh and Karthikeyan Kandan

School of Engineering and Sustainable Development, De Montfort University, Leicester, UK – yogeshvaran.nagarajan@my365.dmu.ac.uk

Abstract: *Prosthetic Sockets serve as an integral link between the amputee's residual limb and the rest of the prosthesis. Focusing on sustainability (recycling and bio-degradable), we explore the suitability of self-reinforced(sr) PLA and PET composite as alternative materials for manufacturing prosthetic sockets. For this purpose, we performed tensile and flexural testing on commingled woven srPLA and srPET composite. The srPLA exhibits elastic-brittle response having an average failure strain of 2%. In contrast, srPET displays elastic-plastic response with average failure strain reaching up to 20%. The tensile and flexural strength of srPET is 132MPa and 72MPa, respectively. This is on par with the standard prosthetic socket materials including Glass and Carbon fibre reinforced composite with thermoset matrix. Therefore, srPET could be the realistic alternative for manufacturing sustainable prosthetic sockets. In contrast, the srPLA has inferior mechanical properties to that of standard prosthetic socket materials. Since the srPLA composite has recyclability and bio-degradability, it can be used to manufacture the test or check sockets; thus reducing the plastic pollution due to discarded check sockets.*

Keywords: Prosthetic Socket; Thermoplastic composites; commingled yarn; material property

1. Introduction

A prosthesis is an external device replacing missing or defective body parts. The functional requirement of the prosthesis is to regain mobility. For example, a prosthesis made for a lower-limb amputee consists of three parts namely prosthetic socket, pylon and foot. The prosthetic socket plays a vital role in transferring load between the prosthesis and residuum limb. Specific stiffness & strength, durability, manufacturability and cost are the crucial factors in choosing the appropriate material for the fabrication of functional prosthetic sockets. Thermoplastic polymers such as High-Density Polyethylene (HDPE) and Polypropylene are the first candidate material for a prosthetic socket when considering cost and ease of manufacturing. In general, thermoplastic sockets are less durable due to inadequate specific strength and stiffness to withstand the maximum normal and shear stresses developed within a socket by the action of amputee weight and gait.

On the other hand, laminated composites made from thermoset polymer matrix reinforced with fibres such as Carbon and Glass are the best candidates for socket materials due to their excellent specific stiffness and strength. A plethora of research has been conducted to establish the right combination of matrix and fibre reinforcement to fabricate the laminated prosthetic socket. Phillips and Craelius [1] explored 24 different combinations of laminates (eight different lay-up materials and three types of resins) to use for the prosthetic application. The Ultimate Tensile Strength (UTS) of these laminates has been further classified as Low-range $(18 - 24\,\mathrm{MPa})$, middle-range $(67 - 109\,\mathrm{MPa})$ and high-range $(236 - 249\,\mathrm{MPa})$ materials. Furthermore, there are notable efforts to utilize sustainable reinforcement fibre such as Jute to fabricate prosthetic sockets. Andrew et al. [2] conducted a feasibility study with renewable materials like plant-oil resin with plant fibre for the replacement of the traditional socket material. Similarly, Qahtan et al. [3] measured the tensile property of the polyester resin with a combination of Jute, carbon, glass and perlon reinforcement.

Recently, additive manufacturing is also deployed to 3D print the prosthetic socket using a range of polymers. Meredith et al. [4] fabricated the PLA based 3D printed socket with a combination of epoxy and fibreglass for better properties. Similarly, Merel et.al [5] uses tough PLA to print sockets for overcoming the cost of high-performance sockets. Digital Manufacturing enables ease in fabrication, controlled weight and cost of the socket. However, there was a lack of strength in these 3D printed on compared with that of traditional prosthetic socket materials.

Current manufacturing approaches, utilizing bulk polymers and laminated composites, either do not meet the requirements of accessible custom-specific prostheses with multifunctionality (subtractive manufacturing technologies, including extensive use of computer-aided design and manufacturing techniques, often do not achieve a custom-fit) or lead to a very expensive solution which most of the amputees cannot afford (high-performance prostheses made using composite technology often required the expensive raw materials and extensive tooling). Even additive manufacturing techniques which were originally thought to be able to overcome the drawbacks of existing manufacturing approaches (due to their ability to fabricate complex 3D geometries and structures) could not provide a better solution to this problem. Uptake of 3D printing for the manufacturing of functional prostheses is mainly hindered by the longer manufacturing time, insufficient strength and stiffness of the product and cost (capital plus material) involved in it. Therefore, the main objective of this study is to explore alternative materials for fabricating affordable prosthetic sockets. For this purpose, we explore self-reinforced polymer (srP) composite as a prosthetic socket candidate material. The srPs has been used in a wide range of application in the automotive, aerospace and construction industries. The further driving force for the srP is the prospect of producing lightweight structures as the density of the srP is lower than the bulk polymers. The srP has greater potential in environmental benign (ease in recycling via reprocessing in the melt) and has got greater freedom in shaping and designing complex shapes. The properties of srP highly depend on the fabrication methods and the architecture of the used fabric.

The fibre reinforcement in srP is a highly orientated version of the same thermoplastic polymer from which the matrix is made. The reinforcing fibres and matrix fibres are commingled in srP yarns which allows the matrix to be melted to exhibit a perfect bond between the fibres. Thus, the use of srPs eliminates the need for the resin infusion step used in standard composite laminate manufacturing techniques making this process even quicker. Reinforcing fibres (those which retain their integrity during the curing process) in srP yarns enables a step-change in the material failure strength – an order of magnitude higher than that of 3D printed plastics and bulk thermoplastics. In this study, we perform mechanical characterization of polyethene terephthalate (PET) and polylactic acid (PLA) based srP composite to evaluate their suitability as a candidate material for prosthetic socket application. The self-reinforced-PET (srPET) composite offers recyclability, whilst the self-reinforced-PLA (sr-PLA) composite exhibits 100% bio-degradability.

The organization of this paper is as follows. First, we outline the srPLA and srPET laminate manufacturing protocol to fabricate coupons for mechanical testing. Second, we describe the tensile and flexural response of srPLA and srPET laminates. Finally, we compare the mechanical properties of srPLA and srPET with that of traditional prosthetic socket materials.

2. Methodology

2.1 Manufacturing Process

Compfil APS supplied Twill 2/2 woven fabric made from SrPET and SrPLA for this study. The supplied srPET and srPLA woven fabric had a tex value of $750\ \mathrm{g/m^2}$ and $360\ \mathrm{g/m^2}$, respectively. A total of six woven fabric having the size of $400\ \mathrm{mm} \times 400\ \mathrm{mm}$ was cut from each roll for composite manufacture. Before vacuum consolidation, the woven fabrics were dried at 50℃ for 24 hours in the oven to remove moisture. A standard vacuum bag procedure is followed to cure the srPET and srPLA composite. It consists of stacking 6 layers of woven fabric on top of the base plate and covered with the vacuum bag. The silicone sealant tape was used to seal the edges of the vacuum bag to achieve 80% vacuum during the consolidation process. The whole assembly was placed inside the convection-type composite curing autoclave supplied by the Easy Composite. We programmed the autoclave as per the curing cycle shown in Fig (1). The vacuum pressure has been maintained throughout the process. The cured laminates were retrieved from the autoclave after it cooled down below 100℃. The optical microscopy images shown in Fig 2 demonstrate that the commingled matrix is perfectly encapsulating the reinforcing fibres in both srPET and srPLA composite laminates. These optical images also show no voids demonstrating the successful use of the vacuum consolidation process of laminates.

Figure 1 Typical cure cycle employed to fabricate srPET and srPLA laminates. Photographs of the (a) srPET and (b) srPLA woven fabric and cured composite laminates.

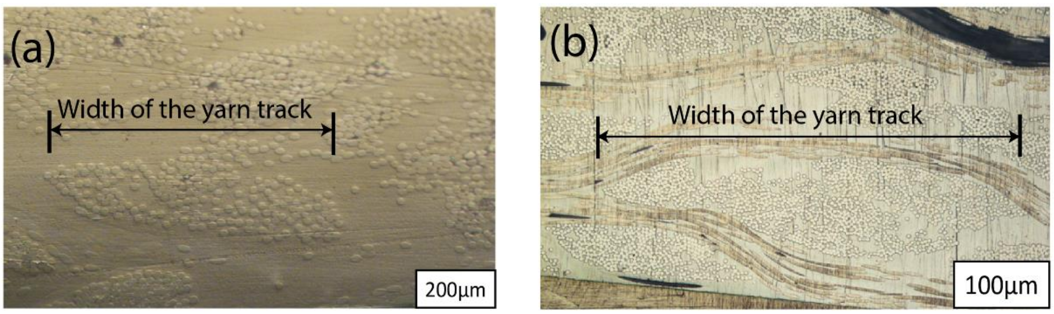
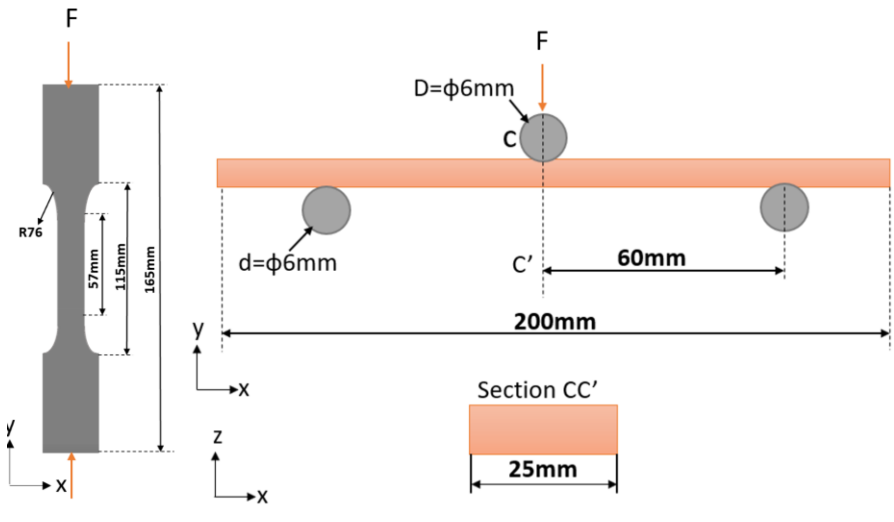


Figure 2 Optical images showing the cross-section of (a) sr-PLA and sr-PET laminates.

2.2 Specimen preparation:

Standard screw-driven Instron 3369 universal testing machine is used to perform the mechanical tests. Tensile tests were carried out per ASTM D638 standard. Tensile test samples were laser cut from the composite laminates, as per dimensions shown in Figure 3a, using an Epilog Laser cutter. Woven laminate samples were tested in both weft and warp directions (see Figure 1) at a cross-head speed of 1mm /min. Before the testing, the thickness and width of each sample were measured using a digital vernier calliper. During the testing, the load and displacement were monitored using a load cell and clip gauge, respectively. These test data have been used to calculate the engineering stress-strain response of the srPET and srPLA woven composites.



(a) (b)

Figure 3 Schematic of the specimen geometry used in (a) tensile and (b) flexural testing.

Flexural tests were carried out as per ASTM D7264 standard to measure the flexural strength of the woven composite laminate. The rectangular type specimen with $200\ \mathrm{mm} \times 25\ \mathrm{mm}$ size was laser-cut from each woven laminate. A three-point type setup was used to apply bending load onto the specimen, see Figure 3b. For this purpose, two rigid rollers were fixed at a $120\ \mathrm{mm}$ distance apart. Then the sample is placed over the two rollers. A third roller was positioned onto the specimen centre and moved downwards to apply bending load, see Figure 3b. During the test, the load and displacement were monitored to measure the flexural response of the woven laminates in both warp and weft directions. Flexural strength is computed using $\sigma = 3FS/2bt^2$, where F is the load, $S = 120\ \mathrm{mm}$ is the span between the loading points; b is the sample width and$t$ is the sample thickness.

3. Results and Discussion

The measured tensile response of srPET and srPLA woven laminates is shown in Fig 4. The srPLA exhibits elastic-brittle response having an average failure strain of 2%. In contrast, srPET displays elastic-plastic response with average failure strain reaching up to 20%. Furthermore, the yield strength of srPET is well defined in the region of 56 MPa. The srPET has higher yield strength (132±5MPa) than that of the srPLA (43±2MPa) composite. Both srPET and srPLA have a similar tensile response in the warp and weft direction of weaving. This is due to good adhesion at the fibre-matrix interface and between the layers during the vacuum consolidation process.

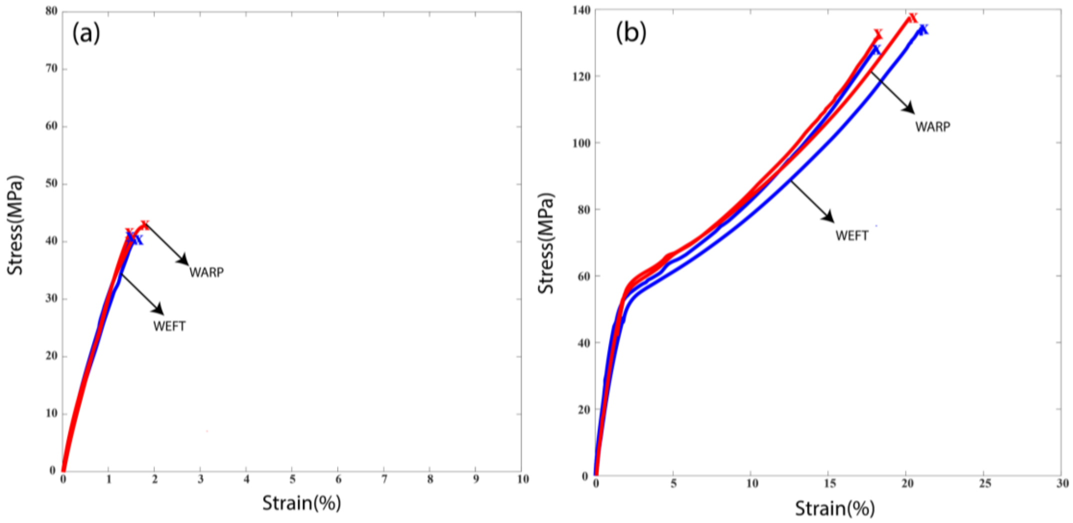


Figure 4: The measured tensile response of (a) srPLA and (b) srPET composite laminates.

Table 1 Summary of mechanical properties of SrPLA and SrPET woven composite. Commonly used socket materials and their properties are also included for comparison purposes.

Parameters	srPLA	srPET	CFRP	GFRP	PP	HDPE
Number of Layers	6	6	-	-	-	-
Density (ρ, g/cm^3)	1.16-1.30	1.25-1.39	1.50–2.10	1.25–2.50	0.88-1.43	1
Thickness (mm)	2.1	3.7	-	-	-	-
Volume fraction ($\boldsymbol{V_f}$, %)	50	50	53	30	-	-
Young's Modulus ($\boldsymbol{E_1}$, GPa)	3.7±0.03	4.45±0.25	25.5 ± 3.3	7.33+-3.32	1.24	0.65-1
Young's Modulus ($\boldsymbol{E_2}$, GPa)	3.85±0.25	4.35±0.05	-	-	-	-
Strain to failure ($\boldsymbol{\varepsilon_1^f}$, %)	1.6	19	1.50-2.10	7.76±1.10	>5%	>5%
Strain to failure ($\boldsymbol{\varepsilon_2^f}$, %)	1.8	19	-	-	-	-
Failure Stress ($\boldsymbol{\sigma_1^f}$, $\boldsymbol{M}$Pa)	40±0.5MPa	127±4MPa	300 ± 20	65.72± 3.30	37.3	21-30
Failure Stress ($\boldsymbol{\sigma_2^f}$, $\boldsymbol{M}$Pa)	43±02	132±5	-	-	-	-

Table 1 shows the key mechanical properties measured during the tensile and bending test for both srPET and srPLA composite. In this table, we have also listed the mechanical properties of standard prosthetic socket materials. SrPET composite failure strength is higher than the strength of monolithic thermoplastic polymers such as HDPE and PP as well as Glass fibre reinforced composites. More importantly, the failure strain of srPET woven composite is much higher than all socket materials. This means that the srPET woven composites can conform to the shape of the residuum limb and can accommodate fluctuation in the volume of the lower limb. It is a crucial factor to fabricate a prosthetic socket for accurate fitting. In terms of comparison with carbon fibre reinforced composite, the properties of srPET woven composite are inferior in all respect. However, it is well known that the material and fabrication cost of carbon fibre reinforced composite is much higher than srPET composites. Also, the carbon fibre composite with a thermoset polymer matrix cannot be reheated for reshaping the prosthetic socket. Therefore, we conclude that srPET woven composites could be the potential choice for socket material.

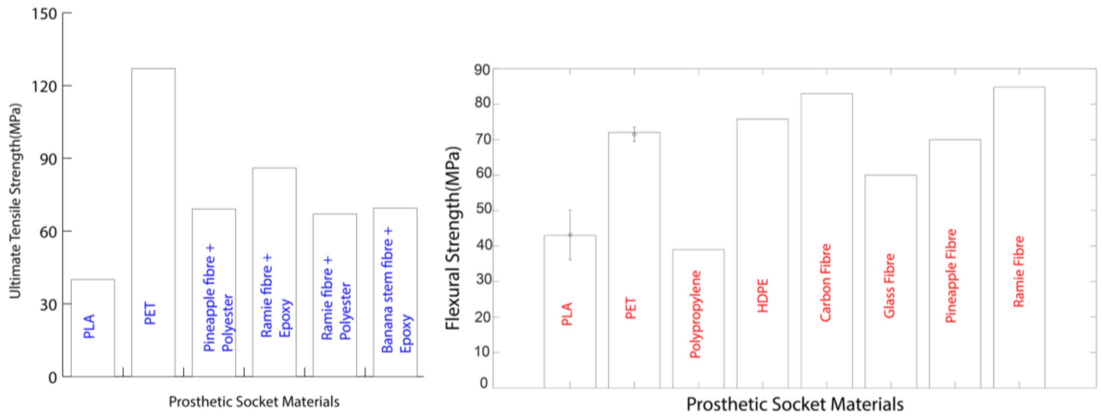


Figure 5 Comparison of Ultimate Tensile strength (UTS) and Flexural strength of srPLA and srPET, alongside regular prosthetic socket materials [1-2, 6-9]

The srPLA composite can compete with standard thermoplastic socket materials (see Table 1) in terms of tensile strength and stiffness. However, the tensile properties of srPLA are inferior to that of standard composites made with carbon and glass fibre reinforcement. Since the srPLA is bio-degradable, it would be prudent to compare the ultimate strength of composites made from plant-based fibres or offer bio-degradability. A bar chart shown in Fig 5 demonstrates that the ultimate strength and flexural of the srPLA woven composite is lower than that of the other plant-based fibres such as Flax, Jute and Ramie. It is worth noting that these fibres were infused with either epoxy or polyester resin to produce composites. It means that the resulting composite is no longer bio-degradable despite using plant-based fibre reinforcements. Despite having inferior strength, the srPLA laminates are ideal candidates for manufacturing test or check sockets to evaluate the socket fit criteria for a particular patient. Often, 3-5 check sockets will be made by the prosthetist to achieve a fit-for-purpose definitive socket. Once the definitive sockets have been made, the unused srPLA test or check sockets can be recycled.

4. **CONCLUSION**:

The study intends to evaluate the mechanical performance of the srPLA and srPET commingled thermoplastic composites. The measured tensile and flexural response of srPET composite is comparable with that of materials used for prosthetic sockets. The srPET offers ease of manufacturing with minimal time compared to standard resin infusion composite fabrication protocol. Therefore, srPET composite could be the ideal candidate for manufacturing prosthetic sockets. The ultimate tensile strength and the flexural response of srPLA composite are inferior to that of traditional prosthetic socket materials. Since the srPLA composite has recyclability and bio-degradability, it can be used to manufacture the test or check sockets; thus reducing the plastic pollution due to discarded check sockets.

Acknowledgements

The authors acknowledge the Frontiers follow-on grant (ref: FF\1920\1\30) offered by the UK's Royal Academy of Engineering for this research.

References

1. Phillips SL, Craelius W. Material properties of selected prosthetic laminates. LWW; 2005;17:27–32.

2. Campbell AI, Sexton S, Schaschke CJ, Kinsman H, McLaughlin B, Boyle M. Prosthetic limb sockets from plant-based composite materials. SAGE Publications Sage UK: London, England; 2012;36:181–9.

3. Hamad QA, Oleiwi JK, Abdulrahman SA. Tensile properties of laminated composite prosthetic socket reinforced by different fibers. Elsevier; 2021;

4. Owen MK, DesJardins JD. Transtibial prosthetic socket strength: The use of ISO 10328 in the comparison of standard and 3D-printed sockets. LWW; 2020;32:93–100.

5. van der Stelt M, Verhamme L, Slump CH, Brouwers L, Maal TJ. Strength testing of low-cost 3D-printed transtibial prosthetic socket. SAGE Publications Sage UK: London, England; 2022;236:367–75.

6. Odusote JK, Oyewo AT, Adebisi JA, Akande KA. Mechanical properties of banana pseudo stem fibre reinforced epoxy composite as a replacement for transtibial prosthetic socket. Association of Professional Engineers of Trinidad and Tobago; 2016;

7. Irawan AP, Soemardi TP, Widjajalaksmi K, Reksoprodjo AH. Tensile and flexural strength of ramie fiber reinforced epoxy composites for socket prosthesis application. Department of Mechanical Engineering University of Malaya, Malaysia; 2011;

8. Odusote JK, Oyewo AT. Mechanical properties of pineapple leaf fiber reinforced polymer composites for application as a prosthetic socket. 2016;7:125–39.

9. Schneider C, Kazemahvazi S, Åkermo M, Zenkert D. Compression and tensile properties of self-reinforced poly (ethylene terephthalate)-composites. Elsevier; 2013;32:221–30.

10. Monette D, Dumond P, Chikhaoui I, Nichols P, Lemaire ED. Preliminary material evaluation of flax fibers for prosthetic socket fabrication. American Society of Mechanical Engineers Digital Collection; 2021;143.

11. Nurhanisah MH, Hashemi F, Paridah MT, Jawaid M, Naveen J. Mechanical properties of laminated kenaf woven fabric composites for below-knee prosthesis socket application. IOP Publishing; 2018. p. 012050.

