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Mgr inż. Magda Dziaduszewska [1], Mgr inż. Marcin Wekwejt[2]

[1,2] Gdańsk University of Technology, Faculty of Mechanical Engineering, Department of Materials Engineering and Bonding, Narutowicza 11/12, 80-233 Gdańsk, Poland

[1] magda.dziaduszewska@gmail.com, tel. 693244622

CAMPOSITES IN ENERGY STORING PROSTHETIC FEET

MATERIAŁY KOMPOZYTOWE W ELASTYCZNYCH PROTEZACH STÓP

Magda Dziaduszewska, Marcin Wekwejt

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STRESZCZENIE

Kompozyty wzmocnione włóknami węglowymi i szklanymi stały się podstawowym materiałem wykorzystywanym w produkcji elastycznych stóp protezowych (ESPF/zawracające energię/sprężyste protezy stóp). Ich właściwości zapewniają stabilną i lekką konstrukcję umożliwiającą gromadzenie, magazynowanie i uwalnianie energii w trakcie chodu, zapewniając tym samym wzrost efektywności chodu. W zależności od przeprowadzonej modyfikacji kompozytu (dobór włókien, formy, rodzaju łączenia, masowej zawartości) oraz od konstrukcji protezy, stopa uzyskuje różną sprawność będącą stosunkiem energii uwolnionej do energii zgromadzonej. W artykule scharakteryzowano elastyczne protezy stóp pod kątem właściwości mechanicznych i funkcjonalnych, porównano właściwości włókien i żywic wskazując materiał najlepiej spełniający wymagania wobec elastycznych protez stóp. Przedstawiono także możliwe modyfikacje materiałów kompozytowych, które wpływają na właściwości materiału i pracę stopy. Przedstawiono także przegląd wybranych stóp protezowych dostępnych na rynku z uwzględnieniem materiału z którego są wykonane i sprawności jaką wykazują.

ABSTRACT

Composites reinforced with carbon and glass fibers have become the commonly used material in the production of energy storing prosthetic feet (ESPF/elastic feet prostheses). Their properties ensure a stable and light structure that allows for accumulation, storage and release of energy during walking, thus ensuring an increase in gait efficiency. Depending on the modification of the composite in terms of fiber selection, their form, type of combination and mass content, and the design of the prosthesis, the foot obtains different efficiency as the ratio of energy released to energy accumulated. The article characterizes ESPF's in terms of mechanical and functional properties, compared properties of fibers and resins indicating the material that meets best the requirements towards elastic feet prostheses. Possible modifications of composite materials that influence the material properties and the work of the foot are also presented as well as an overview of selected ESPF prosthetic feet available on the market.

SŁOWA KLUCZOWE

Materiały kompozytowe, włókna węglowe, elastyczne protezy stóp

1. INTRODUCTION

The prosthetic foot is considered the second most important prosthesis module (the first one is the socket). Through contact with the ground, it determines how the whole prosthesis will behave. It affects the patient posture, correctness of walking, the degree of loading of the remaining joints. Feet differ in severity of disability, functionality and design or material they are made of. Their structure combines two basic components: the heel and the keel [1].

The development of prosthetic feet aims to increase the range of mobility. Traditionally, the basic and primary role of leg prosthesis was to extend the stump to the ground and provide the patient with balance (wooden prostheses). At the beginning, prostheses were made of wood and using metal alloys [2]. These materials caused limitations due to their high weight, low durability and corrosion. An example of the next generation was the "SACH" foot (Solid Ankle, Cushioned Heel), in which a wooden element combined with an aluminum element were joining the foot and the socket. This solution not only provided a supporting function, but also basic mobility [3]. Further improvements were related to the introduction of spherical joints replacing the ankle, but the foot itself remained heavy and stiff. The use of composite materials turned out to be a breakthrough in the history of foot prostheses, since it enabled storage and release of energy during use. Launch of the Seattle Foot (U.S. Pat. 4547913) in 1981 has started the idea of ESPF. The resilient properties of the material provided additional mobility and convenience for users [3,4].

The aim of this paper is to characterize flexible foot prostheses in terms of the material from which they are made of. The mechanical and functional features of flexible prostheses, as well as the characteristics of composite materials with the possibility of their modification have been presented. An overview of selected models of active foot prostheses is provided, and it is determined which fibers and what modification is the most beneficial for durable, light and highly elastic foot prostheses.

2. CHARACTERISTIC OF ENERGY STORING PROSTHETIC FEET

ESPF's, called also Elastic Feet or Active shock feet, are dedicated for people with good and very good physical activity and expectation of a high efficiency prosthesis to perform this activity. The efficiency is defined as the ratio of energy released to energy stored during the heel contact with the ground [3, 5]. During the ground contact, the heel is loaded in compression and slowly unloaded with energy realising in mid-stance. When the foot moves into dorsiflexion, the keel starts to store the energy. It allows to achieve effortless forward propulsion acting like a catapult pushing forward into preswing [3, 6]. Elastic materials help patients to perform daily activities involving fast walking, jogging and climbing stairs with less energy effort. ESPF's vary in performance levels and their use depends on the patient's health condition. For patients with greater mobility, feet with higher efficiency are dedicated. Elastic feet are characterized by the mechanical and functional features listed in Table 2.1.

Tab 2. 1 Mechanical and functional features of elastic feet prosthesis [7-11].

Mechanical/structural [9-11]	Functional [7, 8]
➢ High yield strength ➢ High tensile strength ➢ High compressive strength ➢ Low density ➢ High shear strength ➢ High elastic modulus ➢ High corrosion resistance ➢ Flexibility ➢ Durability	➢ High shock absorption ➢ High level of energy storage and return ➢ Low weight ➢ Smooth toe-off ➢ High push-off ➢ High ground contact ➢ Long duration of foot flat during the stance phase ➢ High stability ➢ Easy to clean ➢ Aesthetic

3. THE FUNCTION OF COMPOSITES IN FEET PROTHESIS

3.1. COMPOSITE SELECTION FOR ENERGY STORING FEET PROSTHESIS

Composite materials used, among others, in foot prostheses are layered materials composed of at least two complex components: fiber (reinforcement) and adhesive (resin, matrix). The fiber is a reinforcing element and carries most of the loads while the resin is a continuous component, bonding the fibers in the structure element. The main feature of the composites is high strength at low specific gravity and the possibility of modifying them - depending on the needs, we can modify the composites with a variety of reinforcements, type of resin or method of combining the substrates, thus obtaining the corresponding properties [1-3, 12].

Commonly used fibers for prosthetic feet are glass, carbon and aramid fibers that meet the requirements for prostheses best. The most commonly used resins are epoxy resins [2] (Tab. 2.2).

Tab. 2. 2 The comparison of main fibres, matrix and composites mechanical properties [13-15].

Properties	Density ρ [g/cm^3]	Tensil strength Rm [MPa]	Young modulus E [GPa]
FIBRES			
Glass	2,5-2,6	1350-4900	60-90
Carbon	1,6-2,0	2800-5490	230-588
Aramid (Kevlar)	1,44-1,47	2900-3450	59-179
MATRIX			
Polyester	1,1-1,4	45-85	1,3-4,5
Epoxy	1,2-1,4	40-85	2,1-5,5
COMPOSITES			
Glass fibres/ polyester	2,0	1250	48
Carbon fibres/ epoxy	1,5	1050	180
Aramid/epoxy	1,4	1250	76
OTHER			
Steel	7,8	1000	200

Glass fibers are characterized by high tensile strength at a relatively low Young's modulus and high modulus of shear. This means that they are robust, but little stiff and relatively heavy. Therefore, the construction of lightweight, responsible constructions uses stiffer, lighter and more durable, but much more expensive carbon and aramid fibers. Aramid fibers have the highest tensile strength and high elongation-to-break ratio (1.6-3.6%). They are also characterized by a very good fatigue strength, abrasion resistance, high energy destruction and good electrical properties. However, they exhibit low compressive strength, which means the need for additional reinforcements in the form of glass or carbon fibers [15]. What is more, compared to other composite elements aramid fibres are the most expensive.

Carbon fiber is characterized by a very high specific strength, i.e. strength to weight ratio, good vibration damping and abrasion resistance [2]. These are particularly important features for prosthetics. The limb prosthesis must be lighter than a healthy limb. Reducing the weight of the prosthesis reduces the energy expenditure of the muscles needed to move the foot and thus reduces the high metabolic cost [7, 16]. Compared to steel or other light metal materials such as aluminum, carbon fiber has higher resistance to fatigue and stiffness. It is characterized by low thermal expansion (which allows maintaining stable dimensions), high tensile strength and chemical stability. What is more, carbon fiber composites are characterized by aesthetics and unique appearance (black and shimmering color) [17].

Carbon fiber, when combined with an epoxy resin, is one of the lightest and most durable materials [15]. Good adhesion of epoxy resins to the substrate provides greater adhesive strength and a better degree of fiber filtration compared to a polyester resin. This property provides materials with less shrinkage due to a longer curing process, during which microcracks and high internal stresses are not produced.

3.2. COMPOSITE MATERIAL MODIFICATION AND ITS INFLUENCE ON ELASTIC RESPONSE

In addition to the selection of composite elements (resin and fibre), these materials can be modified according to the arrangement of fibers, mass content and method of joining the individual layers. The determinant of the modification is to obtain the expected functionality of a given prosthesis. Scheme 4.1 presents composite materials and elements that may be subject to modification [1, 3, 4].

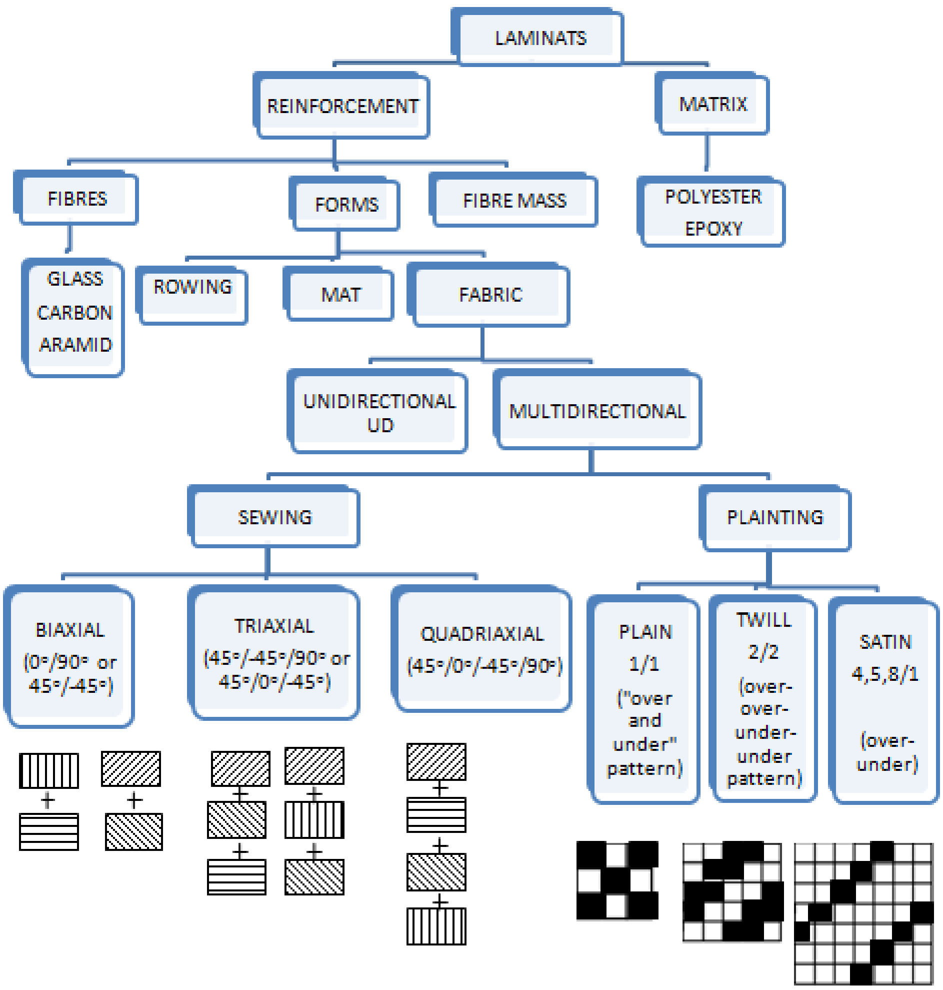

Fig 3. 1 Types of reinforcement, matrix, forms of fibers and styles of bandwidth in multilayered composites (laminates).

The following commercial forms of fibers are distinguished: roving, mat and fabric (multidirectional and unidirectional - UDC) with several styles of bandwidth connections: differing in number of layers and the way they are combined (at various angles or in different ways of sewing/plaiting).

Along with the increase in carbon content, the strength properties of fibers change [1]. The higher the K-level, the more rigid foot must be, the closer the braid and the higher the density [10, 18]. More flexible forefoot permits and easier roll-over [13]. Unidirectional composites loaded in the fiber direction are more resistant to wear changes. Higher susceptibility to such changes is exhibited by composites containing layers of various structure and orientation, e.g. reinforcement from mats and fabrics [13]. The highest strength and the highest Young's modulus are achieved in unidirectional composites loaded towards the fibers. Fibers arranged in the form of fabric are the most effective [3, 4].

Plain type braiding is stable but not flexible enough, twill weave type provides greater flexibility, but the fiber can move, while the satin weave fabric is very flexible, prone to lay in complicated areas, with large curvatures [12, 14]. The arrangement of all fibers in the direction of the tensile load action results in a huge increase in strength and stiffness. The condition for obtaining optimum properties of the composite is a perfect connection of the matrix and the reinforcing phase (good adhesion of fibers and matrix) [1].

The mass content of fibers is calculated from EN ISO 12215-5: 2008 and depends on the type of reinforcing layers (staple fibers, roving fabric, matte fabrics, multidirectional fabrics, unidirectional fabrics) and on the production technology of a given laminate layer (open molding, forming vacuum). Knowledge of the mass content of fibers allows us to calculate the thickness and mechanical properties of individual layers [19].

4. ENERGY STORING FEET MARKET

The market for lower limb prostheses offers foot prostheses for all levels of activity (K - the 4-level functional classification system of the subject of the lower limb amputation and the medical necessity of certain prosthetic components). Each K level corresponds to the efficiency range of the foot. We distinguish conventional feet (SACH, single and multiple axis) for people with low mobility and energy storing feet for active people. Table 4.1 presents the models of feet prosthesis offered by 3 selected, leading companies producing prosthetic components (RRF, Otto Bock, Ossur) along with the material from which they were made of [20-23].

Tab.4. 1 Examples of chosen types of feet models, detailing their efficiency and the material from which they were made.

Types of feet	K-level	Efficiency [%]	Product Offering	Material
Conventional: SACH, single and multiple axis	K1	25	SACH foot (RRF, Ossur, Otto Bock)	Rigid keel (wooden or plastic) +noncompressible foam (plastic or rubber material)
Energy storing	K2	30-50	Equilibrium® (RRF)	Carbon/glass fiber
			Terion 1C1® (Otto Bock)	Glass fiber
			BK- Bundle® (Ossur)	Glass fiber
	K3	45-60	Roadflexion® (RRF)	Carbon fiber
			TLM Food® (Otto Bock)	Carbon fiber
			Re-Flex Shock® (Ossur)	Carbon fiber
	K4	55-70	Roadwalking® (RRF)	Carbon fiber
			Triton 1C61® (Otto Bock)	Carbon fiber
			Vari-Flex® (Ossur)	Carbon fiber

Feet in the K1, intended for people who exhibit daily activities involving gentle, steady walking with the use of a walking aid (moving around at home, modest walking in the community) doesn't need a high level of energy storage and return and are made of wooden or plastic keel as well as sysnthetic rubber heel wenge.

For people who overcome the basic environmental barriers (curb, stairs) (K2) manufacturers offer products made mainly of glass fiber or carbon/glass fiber. Feet in the K3 and K4 are made of carbon fibers, which exhibit the highest energy return.

In the context of composite material modifications (forms, fiber mass, bending) used for foot prostheses, information about them are usually trade secrets of the given companies and testify to the unique value of the product.

5. CONCLUSIONS

Due to their ability of storing and releasing energy, compared to conventional feet prostheses, ESPF's are especially dedicated for active people. The most important features of elastic feet are high strength to density ratio, possibility of shock absorption and ability of smooth roll over. The type of fiber, the number of layers, the way of laying and the method of combining the substrates determine the efficiency of the foot. The material adjustment for a given foot depends on its function. The higher the K-level, the more rigid foot must be, the closer the braid and the higher the density. An overview of energy storing feet market presents that glass fibre or carbon/glass fibre are used for medium active patient (K2), while carbon fibre combined with an epoxy resin, due to the lightest and most durable features is the most common material for active and very active patients (K3, K4). In the literature there is little information on the exact modification of composites (type of plaiting, mass content of given fibers) because it is a highly guarded know-how of companies. However, the key challenge is to properly select the material to the patient's capabilities. Therefore the research of materials modification combined with gait analyses of amputee remain the significant issue to improve their mobility and comfort in daily life.

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