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Composite Materials for Orthotics and Prosthetics

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INTRODUCTION

In the ever-changing field of orthotics and prosthetics, recent advancements have been achieved with the use of new materials and resins. In the Spring of 1981, a study project was initiated in an attempt to learn the proper use of these high-tech materials. Data was accumulated from various chemistry and physics texts on the characteristics of composite materials, specifically carbon, Kevlar®, and fiberglass. The next study phase was to fabricate a series of laminated cylinders using composite and stockinette combinations with numerous resins. The cylinders were static-tested for resistance to tension and compression, along with strain and fatigue characteristics. The final research stage was the fabrication of prosthetic appliances for field testing. The lay-up, resin type, total weight, and the author's subjective opinion of every prosthesis was recorded over a 2½ year period. The intent of this article is to present the rationale for specific applications of composites and resins for prosthetic/orthotic appliances, based on field study and the aforementioned research, in conjunction with established West German fabrication techniques and technology.

STRESS

Evaluation of the principal stresses and forces involved in an orthopedic appliance will greatly assist in proper composite choice and application. The principal forces to consider are tension and compression.

Within the socket wall, tensile and compressive resistance forces are responsible for maintaining strength, form, and structure (Figure 1). As body weight is transferred through the socket walls, the outer surface is faced with a specific tensile load, while the inner wall is subjected to an equal and opposite compressive load.

An intermediate layer of material separating the inner and outer wall serves as a transition medium between the opposing forces. The increased distance between the inner and outer wall is directly proportional to increased resistance to fracture, fatigue, and failure. While examining the applied forces on an appliance during the walking cycle (Figure 2) at heel strike, a compressive force is evident at the posterior aspect of the structure, while an equal and opposite tensile force is exerted anteriorly. At flat foot, the forces remain compressive posteriorly and are inverted to a compressive force along the anterior aspect. At toe off, the posterior force transforms to a tensile stress, with the anterior force remaining compressive. Other forces involved with an orthopedic appliance are torque, shear, and impact stress; therefore, they must be considered and appreciated.

With all the specific and individual forces and stress involved with an orthopedic structure, the required properties of a reinforcing composite would be:

- lightweight
- strong under tension
- strong under compression
- flexible, to absorb torque
- stiff, to resist bending and shear stress

- durable, to resist fracture under impact
- capable of resisting stress in all planes
- cost effective
- easy to apply

COMPOSITES

The three composites tested and presently being used in the orthopedic industry are: 1) fiberglass; 2) Kevlar® (Aramid®); and 3) carbon (Graphite). The advantages of one composite over another is due to each material having completely different properties and characteristics (Table 1).

Fiberglass is by far the most common and economical composite. Although the heaviest material of the three, it is easy to saturate with resin and very easy to obtain in many forms and qualities. The principal properties of fiberglass are its durability and flexibility, due to the fibers being twice as strong under compression as compared to the fiber strength under tension.

Kevlar® is the lightest and most expensive composite. It provides an excellent resistance to fracture under impact and can absorb high loads of torque and stress. These desirable properties are, however, compromised, as Kevlar® is very poor in maintaining structure or form under load; it is five times weaker under tension than it is under compression. In addition, Kevlar® is extremely resistant to chemicals and very difficult to saturate with resin.

Perhaps the most valuable composite to orthopedic appliances is carbon. Almost as light as Kevlar®, it is very stiff and able to hold its shape under stress due to its impressive strength under both tension and compression. The structural compromise of the carbon fibers is that the stiffness creates brittleness and a poor resistance to impact.

A very important consideration when working with composites is one of the principles of the fiber—all the available strength and characteristics of a composite fiber are displayed and produced only along the length of the fiber.

To achieve the highest degree of fracture resistance with a composite structure, the angle of the fibers in relation to the applied stress is imperative. With regard to bi-directional (woven cloth) or uni-directional (tape) composites, these materials are excellent for localized strength, but are capa-

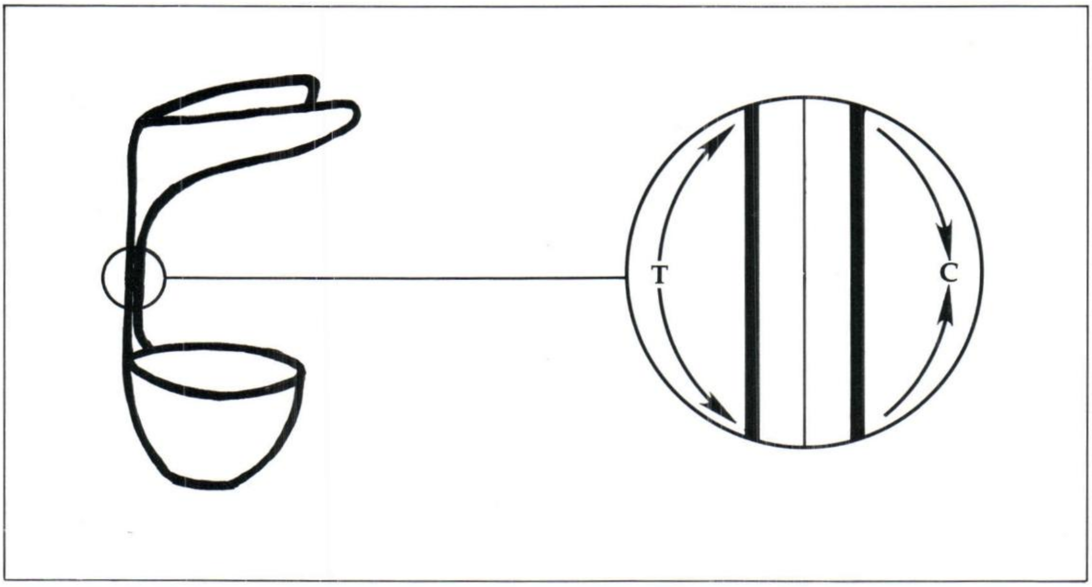

Figure 1. Within the socket wall, a tensile stress is exerted on the outer surface, while a compressive stress is exerted on the inner surface. At the center between the two surfaces, there is an imaginary line called the "Null Zone," which is the transition point of compression and tension. This produces an 'I-Beam' effect. The increased distance between the inner and outer wall is directly proportional to increased resistance to fracture.

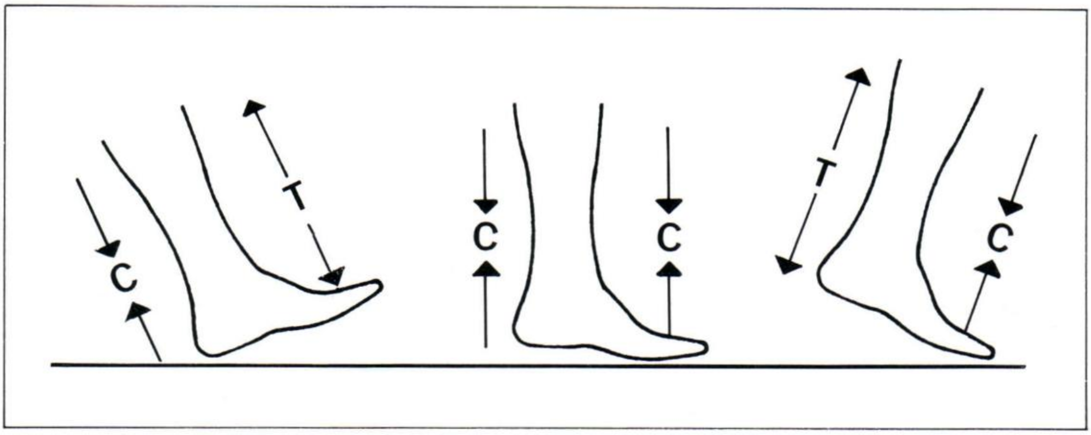

Figure 2. The forces transmitted through the anterior and posterior aspects of an orthopedic appliance fluctuate from tensile (T) to compressive (C) during the walking cycle due to the rotational movement caused by the floor reaction. The stress of torque, shear, and impact have not been included in this diagram, but are present and must be dealt with when reinforcing an appliance.

ble of providing single composite properties in one direction alone, and the fibers of the composite must be positioned perpendicular to the stress plane to be effective. To achieve uniform strength, with equal resistance to fracture in all directions, a "quasi-iso-trophic" composite is required. This can be achieved by applying composites in a mat or knit form, which places composite fibers in a three-dimensional/multi-plane manner. Considering the unique properties of each composite, the most effective application for these fabrics is obtained by blending the materials to produce a "quasi-iso-trophic hybrid" composite. This provides a combination of the most desirable properties of each fiber into a single medium, resistance to torque, shear, compressive, tensile, and impact stress from any possible direction. The ultimate blend is a hybrid of carbon-Kevlar®. Carbon provides lightness and stiffness; Kevlar® provides lightness, impact and torque resistance.

A blend of carbon-fiberglass can also achieve extremely high resistance to fracture with a very good weight to strength ratio, and is somewhat more cost effective. This hybrid displays the stiff and lightweight carbon properties combined with the inexpensive, flexible, and durable fiberglass characteristics.

Tensile and Compressive Values (10^3 PSI) of Static Tested Samples of Kevlar,® Fiberglass, and Carbon

	Fiberglass	Kevlar®	Carbon
Tensile	10	15	13.2
Compressive	5	3	10.6

(Values 10^3 PSI to point of fracture)

Table 1.

SOCKET REINFORCEMENT (Table 2)

The choice of materials to be used for socket fabrication depends entirely upon the patient's demands and requirements.

Varying Lay-up for Prosthetic Appliances

Type of Socket	½ oz. Dacron	Carbon/Glass	Carbon/Kevlar®	Carbon Type	Fiberglass/Nylon Stockinette	Stretch Nylon Stockinette	80/20 Acrylic 2% hardener	Carbon Acrylic 2% hardener
Below Knee Socket	1 inner layer			1 layer at PTB	3 intermediate layers	1 outer layer	300 grams	
Heavy Duty BK Socket	1 inner layer	2 intermediate layers		1 layer at PTB	1 intermediate layer	1 outer layer		300 grams
Super Duty BK Socket	1 inner layer		2 intermediate layers	1 layer at PTB	1 intermediate layer	1 outer layer		300 grams
Below Knee Flexible Socket	*2 layers fiberglass matting at popleteal fossa	2 intermediate layers		1 layer at PTB	1 inner 1 intermediate layer	1 outer layer		300 grams
Outer Shell for Below Knee					2 inner layers	1 outer layer	250 grams	
Heavy Duty Outer Shell for BK		1 inner layer			1 intermediate layer	1 outer layer		250 grams
Above Knee Socket	1 inner layer			1 layer at ischial level	3 intermediate layers	1 outer layer	400 grams	
Heavy Duty AK Socket	1 inner layer	2 intermediate layers		1 layer at ischial level	1 intermediate layer	1 outer layer		400 grams
*Flexible Socket Frame		2 intermediate layers		*2 layers fiberglass mat	2 intermediate layers	1 inner 1 outer layer		350 grams
Symes Socket	1 inner layer	2 intermediate layers		1 layer at PTB 1 layer at ankle	1 intermediate layer	1 outer layer		350 grams
Heavy Duty Symes Socket	1 inner layer		2 intermediate layers	1 layer at PTB 1 layer at ankle	1 intermediate layer	1 outer layer		350 grams
Knee Disarticulation	1 inner layer	2 intermediate layers		1 layer at condyles	1 intermediate layer	1 outer layer		450 grams
Heavy Duty Knee Disarticulation	1 inner layer		2 intermediate layers	1 layer at condyles	1 intermediate layer	1 outer layer		450 grams
Upper Extremity		1 intermediate layer			1 intermediate layer	1 inner 1 outer layer		250 grams
Heavy Duty Upper Extremity			1 intermediate layer		1 intermediate layer	1 inner 1 outer layer		250 grams
Lower Extremity Childrens Socket		1 intermediate layer			1 intermediate layer	1 inner 1 outer layer		200 grams

Table 2.

All appliances are most durable with five layers of reinforcing composite. The level of durability is controlled by the type of composite used and the method in which it is applied with the applicable resin.

Fiberglass reinforced stockinette will be adequate for the majority of geriatric amputees. If the activity level requires a "heavy-duty" prosthesis, then carbon-fiberglass knit stockinette is preferred. For a "super-duty" socket, carbon-Kevlar® knit composites will provide the necessary strength. When applied with an inner layer of dacron, an intermediate layer of fiberglass nylon, and an outer layer of nylon stockinette, the total thickness for prosthetic sockets in all activity levels remains a uniform five layers of material.

THE BELOW-KNEE SOCKET (Figure 3)

After determining the activity level of the patient and the required blend of composites, consideration must also be directed toward specific stresses in the socket. Due to the thinness of the socket and the fact that significant stress is applied at the patellar tendon level, a strip of two-inch carbon tape is wrapped around the socket at this level to increase the stiffness and to maintain a rigid AP, ML dimension in the socket. For a supracondylar socket, the medial and lateral ears must be stiff and rigid to maintain suspension; thus, the ears are applied with a layer of three inch carbon tape in a vertical direction. For finishing the shin section, the foam (R300 or 10 lb.) is left in place and sealed with Siegelharz resin. The inner layer of composite is dependent upon the patient's activity level. A layer of fiberglass nylon for normal use, carbon-fiberglass for "heavy-duty" use, or carbon-Kevlar® for "super-duty" application.

For "super-duty" and select "heavy-duty" limbs, vertical strips of carbon tape or a layer of bi-directional carbon cloth at the ankle will increase stiffness, tension, and compression resistance. This inner composite layer is then covered with a layer of fiberglass reinforced stockinette and an outer nylon stockinette, and laminated with the appropriate acrylic resin. The average weight of a below-knee socket using this technique is 275 grams, and the average total weight of the finished prosthesis with a SACH foot is 960 grams.

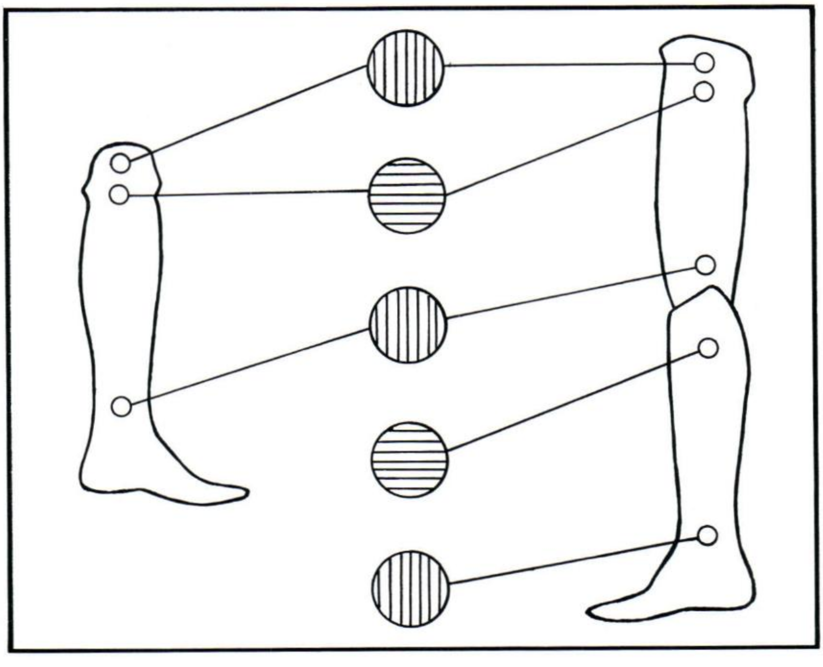

Figure 3. Application of uni-directional Carbon composite on above-knee and below-knee appliances for increased stiffness or specific reinforcement. The Carbon tape is applied to the cast with a small amount of spray adhesive (The acrylic resin will dissolve this during the lamination). The fibers must run perpendicular to the applied stress to hold shape and resist tensile and compressive forces.

THE ABOVE-KNEE SOCKET (Figure 3)

As with the below-knee prosthesis, composite choice for the above-knee socket is dependent upon the amputee's activity level, and a total of five layers of material is preferred. A layer of two or three inch carbon tape is wrapped around the socket at the level of the ischial tuberosity to maintain stiffness and socket shape. In the case of a flexible socket,* the lay-up remains at five layers of composite stockinette, plus two layers of fiberglass matting added between the composite layers to create an "I-Beam," thus increasing strength, stiffness, tension, and compression resistance.

A modular attachment plate is held in place with Siegelharz paste and a lay-up of two layers of fiberglass matting, one layer of fiberglass reinforced stockinette, and a layer of nylon stockinette. For a lower shin section on an exoskeletal type limb, the technique for finishing the below-knee prosthesis is applied over the hollowed-out wood shin portion. The average weight of the above-knee socket is 300 grams; the average weight of an above-knee wood shin prosthesis is 2.5 to 3.5 kilograms, depending upon the foot size and knee unit used (no hydraulic systems were applied).

SYMES AND KNEE DISARTICULATION PROSTHESES (Figure 4)

The disarticulation prosthesis offers the most problems with relation to stress areas and fracture planes. The classic fracture point is the distal anterior and posterior edges of the socket attachment, due to the excessive moments of torque, tensile, and compression stress localized at this section of the prosthesis. Carbon-fiberglass composite is well-suited for the average disarticulation prosthesis, with carbon-Kevlar® meeting the demands for the "heavy-duty" prosthesis.

The localized stress areas at the distal socket attachment points are reinforced with two or three layers of uni-directional carbon tape, ensuring the fibers are running perpendicular to the stress plane. Experience has shown that increasing the total layers of reinforcing carbon tape beyond four layers will only make the prosthesis very stiff and unable to absorb torque and impact. To increase strength, apply one or two layers of fiberglass matting between the carbon layers to produce an "I-Beam" effect better suited to resisting the forces and stresses applied at the ankle or knee.

*Lay-up for the European flexible socket with the width of the medial wall extending from the anterior medial socket edge to the posterior medial socket edge.

ORTHOTICS

The major advantages of laminating a composite orthotic device are its lightness, durability, and ability to be stiff and rein-

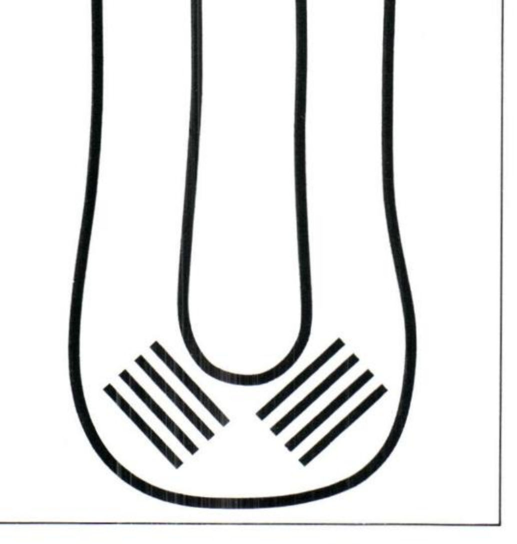

Figure 4. Socket attachment point reinforcement for a disarticulation prosthesis. The Carbon tape is applied with the fibers running perpendicular to the specific stress planes caused by walking (See Figure 2). Overall durability is increased by using a hybrid quasi-trophic composite sandwiched between the Carbon tape.

forced in any area desired. The disadvantages are that it is time-consuming and expensive when compared to vacuum forming. With this in mind, it seems apparent that a small percentage of orthotic wearers (those patients who are over-active, over-weight, or who need extremely specialized orthotic designs where composite characteristics can benefit the orthosis performance) can justify the application of a laminated orthosis. Because custom orthotic appliances are of varied size and shape, and have to withstand different activity demands, standard lay-up charts have not yet been established. Guidelines that do apply, however, include:

1. Keep lay-ups four to seven layers in thickness.
2. Use carbon uni-directional or bi-directional cloth to increase stiffness and resist stress wherever possible.
3. Design "I-Beams" over stress areas (malleoli, achilles tendon) with one or two layers of fiberglass matting sandwiched between carbon fibers.
4. Evaluate and establish all stress areas and fracture planes so they can be properly and effectively reinforced.

For laminating shoe inserts, arch supports, and UCB inserts, two layers of carbon-fiberglass or carbon-Kevlar®-fiberglass stockinette provided very good results.

SPECIAL SOCKET CONSIDERATIONS

On areas of unusually high stress, a structural design to create an "I-Beam" serves as the best response. Within the socket lay-up, fiberglass matting sandwiched between carbon tape or carbon woven cloth will not add significant weight, but will increase strength up to 20 percent and stiffness up to 40 percent. To provide the ultimate reinforcement, fiberglass matting can be replaced with Kevlar® matting sandwiched between the carbon tape or carbon woven cloth. Care should be taken to identify specific stress planes to ensure the carbon fibers are running perpendicular to it.

In areas where 'grinding' may be necessary to ensure a good socket fit, layers of fiberglass matting are applied over the liner ½ ounce dacron sleeve. The fiberglass matting will provide a very light filler that is completely saturated by the acrylic resin and can be easily ground and buffed to a good cosmetic appearance. To finish the socket edges and relief areas, hand finish with 300 grit sand paper; then apply a thin coat of Acrylic Floor Paste and rub into the plastic.

ACRYLIC RESINS

Acrylic resins are a lightweight thermosetting plastic with excellent wetting properties and good inherent strength, making thin ultra-light orthopedic appliances possible. To achieve the ultimate strength and durability of acrylic, the chemical reaction of the resin must follow a set pattern (Figure 5). It is imperative to shake the tin of resin before use; prosthetic resins are a blend of Methylmethacrylate and citric acid, and will separate in the tin. Failure to stir the acrylic will alter the ratio of chemicals being poured into the cup, creating varying and usually unsatisfactory results (i.e., air holes, improper cure times, boiling laminations, brittle sockets, flexible sockets, soft spots, streaking of color pigment). Acrylic resin pigment is recommended to use with acrylic resin. No more than two percent by weight should be mixed, as the pigment is an active plastics softener, and any mixture over two percent will produce streaking and soft spots. The percentage of Benzol Peroxide hardening powder will provide the best results at two percent by weight. The variances are one percent to three percent, and failure to accurately measure this substance will provide disastrous results (i.e., air bubbles, very brittle laminations, boiling laminations). The blending of acrylic thinners should be avoided at all times. Thinners are non-reactive substances that do not participate in the curing process. Ten percent thinners by weight will reduce acrylic strength by up to 20 percent.

Acrylic resin is available in different

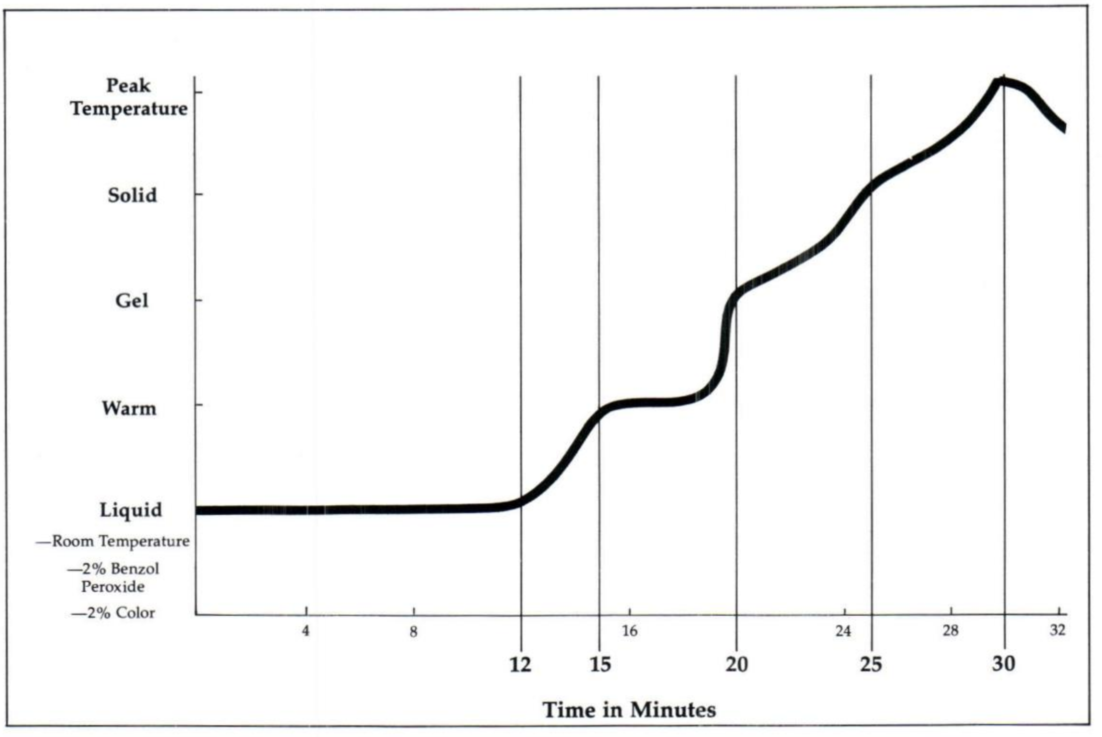

Figure 5. Twelve minutes after 2 percent acrylic pigment and 2 percent benzol peroxide by weight has been blended with the resin, the liquid temperature will rapidly rise to a WARM state. The resin is then poured into the PVA sleeve and impregnated into the material. At the 19 minute mark, the resin will rapidly reach a GEL stage, and the lamination must be completed. The chemical curing process will continue on to the SOLID stage at the 25 minute point and then to a PEAK TEMPERATURE stage at the 30 minute mark. ***To alter this curing pattern in any manner will greatly reduce the strength, durability and working properties of the resin.***

NOTE: This sequence holds true at normal room temperature (21°C.) and normal humidity. If the climate is normal, the resin must be closely monitored and poured into the PVA sleeve when the liquid resin temperature begins to increase. A timer will assist in monitoring the process.

blends, each having its own characteristics and working conditions.

• *80/20 Laminierharz (laminating resin)*—A standard blend of 80 percent rigid and 20 percent flexible resin to be used for vacuum laminations to saturate nylon, fiberglass, and dacron fibers.

• *Elastiharz (flexible resin)*—100 percent flexible resin to be used for vacuum laminations to saturate nylon fibers.

• *Carbonacrylic*—A special blend of 80/20 resin to be used for vacuum laminations to saturate nylon, fiberglass, dacron, and especially carbon fibers (note—carbon acryl will partially saturate Kevlar® up to 85 percent). This resin is designed with a low viscosity for improved saturation and has a higher setting temperature for improved composite bonding. Carbonacrylic resin is not any stronger than regular 80/20 laminierharz; its effect on the carbon fiber is its advantage.

• *Siegelharz (sealing resin)*—A 100 percent rigid resin to be used for bonding common materials and sealing wood and foam. This is the only acrylic resin that can be used without vacuum. For a non-vacuum lamination, blend 30 percent elastiharz with 70 percent Siegelharz with two percent color and one percent Benzol Peroxide paste. This mixture will cure rapidly compared to other acrylic resins.

• *Siegelharz Paste (sealing paste)*—An alternative way to apply Siegelharz, as this is blended into a gel and does not require any fillers. It will set with one percent Benzol Peroxide powder or paste in five minutes to be completely cured in 10 minutes. This material will give an excellent bond between all common materials, will adhere metal joints and attachment plates to sockets, and will serve very well for socket repairs (note—Siegelharz paste will not adhere wood to wood; liquid Siegelharz should be used).

To calculate the amount of resin required for a lamination, a formula has been established for lay-ups consisting of five layers of material:

$$\frac{\text{largest circumference of the cast in centimeters} \times \text{total length of the cast in centimeters}}{\div\, 3} = \text{the total grams of resin required}$$

The total grams required is then rounded off to the nearest 50 (e.g., a final answer of 333 grams will be rounded off to 350 grams).

CONCLUSION

The opportunities and applications for hi-tech composites and acrylic resins in the orthopedic industry are seemingly infinite. Assessment of every patient's orthopedic appliance, concentrating on structural stresses, composite type, and fiber orientation with proper resin application will increase material performance and provide the numerous advantages "hi-tech" materials have to offer.

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