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Material Selection for a Composite Hip Joint

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U.A.E. University
Deanship of Graduate Studies
Material Science and Engineering Program

Material Selection for a Composite Hip Joint

By

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Requirements for the Degree of Master of Science in

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Supervised by

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Abstract

The use of biomaterials in orthopedic surgery has been successfully acceptable in the current medical practice. Total hip joint replacement (THR) is one of the most popular and successful operations in orthopedics. Total hip replacement (THR) has been using metal prosthesis for many years. However, the use of metal implants has two major disadvantages. The first disadvantage is that the stiffness of the metallic prosthesis is relatively high compared to the surrounding, load carrying bone. The elastic moduli of titanium and cobalt-chromium alloy are 110 and 210 GPa, respectively. Whereas the elastic modulus of cortical bone ranges from 15 to 25 GPa. This mismatch between the bone and the stiffness of the implant will cause the degradation of the bone-implant interface, which will lead eventually to loosening and prosthesis fracture. The second disadvantage of metallic prosthesis is the release of harmful metal ions, which may cause hypersensitivity to the patient.

To overcome the stiffness problem and other related metal implants complications, recent advances in design and manufacturing technologies proposed the use of composite materials as an alternative to the metallic implants. The use of composite materials in orthopedic surgery offers a variety of new implant designs. Outstanding mechanical properties; radiolucency, biocompatibility and low weight are the major advantages compared with metals in clinical use today. Composite materials are known as low stiffness materials with mechanical properties close to the properties of bone. The strength and stiffness of composite materials can be varied easily when compared to metals. For example, the strength varies from 70 MPa to 1900 MPa and stiffness varies from 1.0 GPa to 170 GPa. Such tailorability in strength and stiffness could provide a state of stress in the femur closer to physiological level. Thus, it will eliminate the problems of bone-prosthesis loosening and prosthesis fracture.

The main goal of this thesis is to investigate the performance of woven composites for a hip prosthesis made from hybrid materials. For such a purpose, field investigation was conducted locally to establish a realistic ground for the total hip replacement procedures in the U.A.E. This field investigation revealed that the THR cases performed in the U.A.E. are exponentially increasing every year. This increase in the THR cases requires an immediate solution for the problem.

For the purpose of this design, two types of fibers were used to manufacture the specimens. The first type of fiber is the E-glass fiber. The second type of the fiber is the hybrid carbon-aramid fiber reinforced vinyl ester resin. Two types of processing techniques were used to manufacture specimens. The techniques were hot press molding and vacuum infusion. The specimens were then divided into three groups and each group contains eight specimens. Some specimens were kept immersed in a physiological solution for eight weeks, while others were used as virgin specimens.

The evaluation process included mechanical test, weight gain calculation for the glass fiber and the scanning-electron microscopy (SEM) study. In this study, we found that immersion in the physiological solution caused reduction in strength and modulus of the composite materials manufactured by vacuum infusion technique. On the other hand, weight reduction did not occur for the glass fiber manufactured by hot press molding. This is due to the lack of adequate resin available in the fiber-matrix interface. Scanning-electron microscopy (SEM) study examined and showed the fractures' surfaces occurred to the specimen.

Fatigue tests performed on conditioned specimens have shown that the main failure mechanism can be attributed to the poor interface between the fiber and the matrix.

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Abbreviations

UAE:	United Arab Emirates
USA:	United States of America
SEM:	Scanning-Electron Microscopy
THR:	Total Hip Replacement
NSAIDs:	Non-Steroidal Anti-Inflammatory Drugs
AN:	Avascular Necrosis
UHMWPE:	Ultra High Molecular Weight Poly Ethylene
GPa:	Gega Pascal
MPa:	Mega Pascal
KN:	Kilo Newton
ISO:	International Standard Organization
FEM:	Finite Element Method
SiC:	Silicon Carbide
PEEK:	Poly Ethylene Ether Ketone
DGEBA:	Di-Glycidyl Ether of Bisphenol A
DETA:	Di-Ethylen Tri-Amine
PAN:	Poly Acrylonitrile
HM:	High Modulus
HS:	Higher Strength
IM:	Intermediate Modulus
PPD-T:	Poly Paraphenylene Terephthalmide
VI:	Vacuum Infusion
PPS:	Poly Phenylene Sulfide
PEI:	Poly Ether Imide

PAI: Poly Amide-Imide

PSUL: Polysulfone

HDT: Heat-distortion temperature.

Chapter One

Introduction

1.1 Definition:

Orthopedics is a branch of surgery that is primarily concerned with providing the skeletal system with functional preservation and restoration. The skeletal system is a complex system that is responsible for stability and mobility of the human. Bones are very important part of this skeletal system. Bones are the main structural components of the body and they transmit predominately compressive, torsional and bending stresses.

Bones are susceptible to undergo several failures, such as bone fractures, bone tumors, osteoarthritis and osteoporosis. These bone failures can create many complications to the patient, such as severe pain, instability, immobility and discomfort of the patient. Eventually, the patient has to go under joint replacements in order to restore mobility and comfort. Knee joints, shoulder joints and hip joints are common joints that require artificial prosthesis replacement.

Total hip joint replacement (THR) is one of the earliest methods established in orthopedics procedures. Approximately, 10 % of the U.S. populations suffer from Osteoarthritis [1,8]. Since 1960s, the number of the total hip arthroplasty operations has increased exponentially up to 400,000 annually [1,8].

1.2 Background:

Today more than 120,000 artificial hip joints are being implanted annually in the United States. This number is increasing in the rest of the world especially in Europe and Canada. Successful replacement of deteriorated, arthritic, and severely injured hips has contributed to enhanced mobility and comfortable, independent living for many people who would otherwise be substantially disabled. New technology involving prosthetic devices for replacement of the hip, along with advances in surgical techniques, has diminished the risks associated with the operation and improved the immediate and long term outcomes of hip replacement surgery.

Total hip replacement (THR) (Figure 1.1) is most commonly used for hip joint failure caused by osteoarthritis (60 percent); other indications include, but are not limited to, rheumatoid arthritis (7 percent), avascular necrosis, aseptic bone necrosis (7 percent), traumatic arthritis, certain hip fractures (11 percent), benign and malignant bone tumors, the arthritis associated with Paget's disease, ankylosing spondylitis, and juvenile rheumatoid arthritis [1]. The aims of THR are relief of pain and improvement in function. Candidates for elective THR should have radiographic evidence of joint damage and moderate to severe persistent pain or disability. Or both, that is not substantially relieved by an extended course of nonsurgical management. These measures usually include trials of analgesic and nonsteroidal anti-inflammatory drugs (NSAIDs), physical therapy, the use of walking aids, and reduction in physical activities that provoke discomfort. In certain conditions such as rheumatoid arthritis and Paget's disease, additional disease-specific therapies may be appropriate. The patient's goals and expectations should be ascertained prior to THR to determine whether they are realistic and attainable by the recommended therapeutic approach.

Any discrepancies between the patient's expectations and the likely outcome should be discussed in detail with the patient and family members before surgery [1].

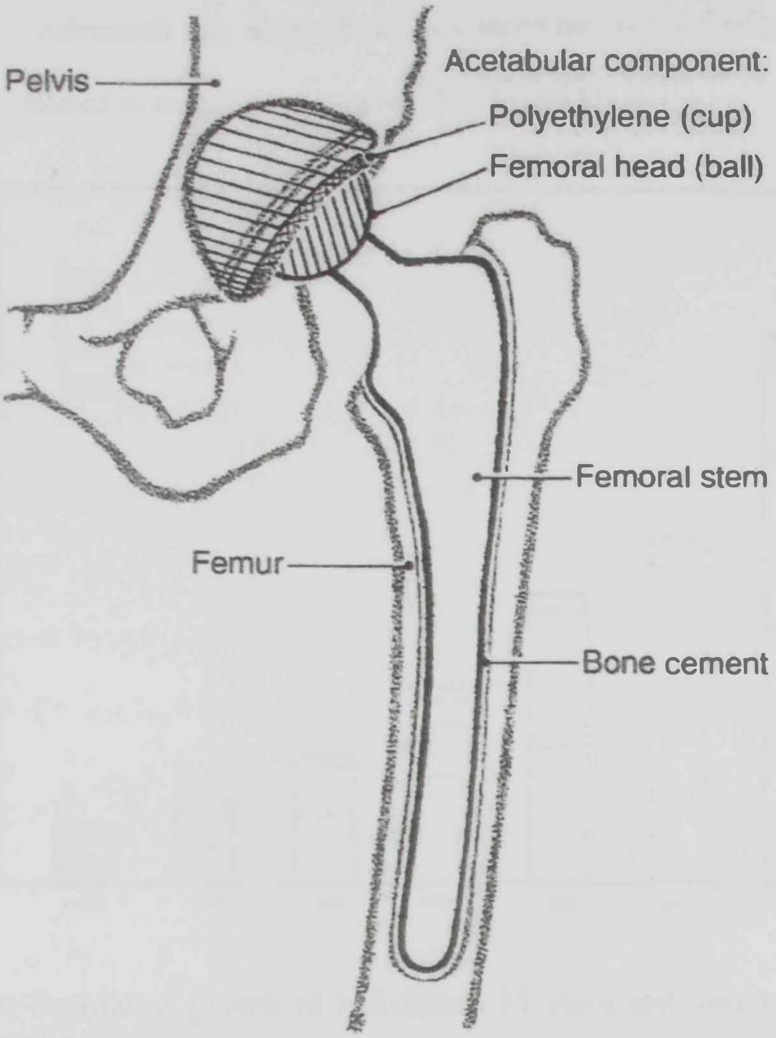

Figure 1.1: A schematic representation of a total hip replacement (THR) [1].

In the past, patients between 60 and 75 years of age were considered to be among the best candidates for the THR. Over the last decade, however, the age range has been broadened to include more elderly patients, many of whom have a higher level of comorbidities, as well as younger patients, whose implants may be exposed to greater mechanical stresses over an extended time course (Figure 1.2). In patients less than 55 years of age, alternative surgical procedures such as fusion and osteotomy deserve consideration. However, there are no data showing that the outcomes of these procedures are as good or better than those from THR when performed for similar indications. Advanced age alone is not a concentration for THR; poor outcomes appear to be related to comorbidities rather than to age [1].

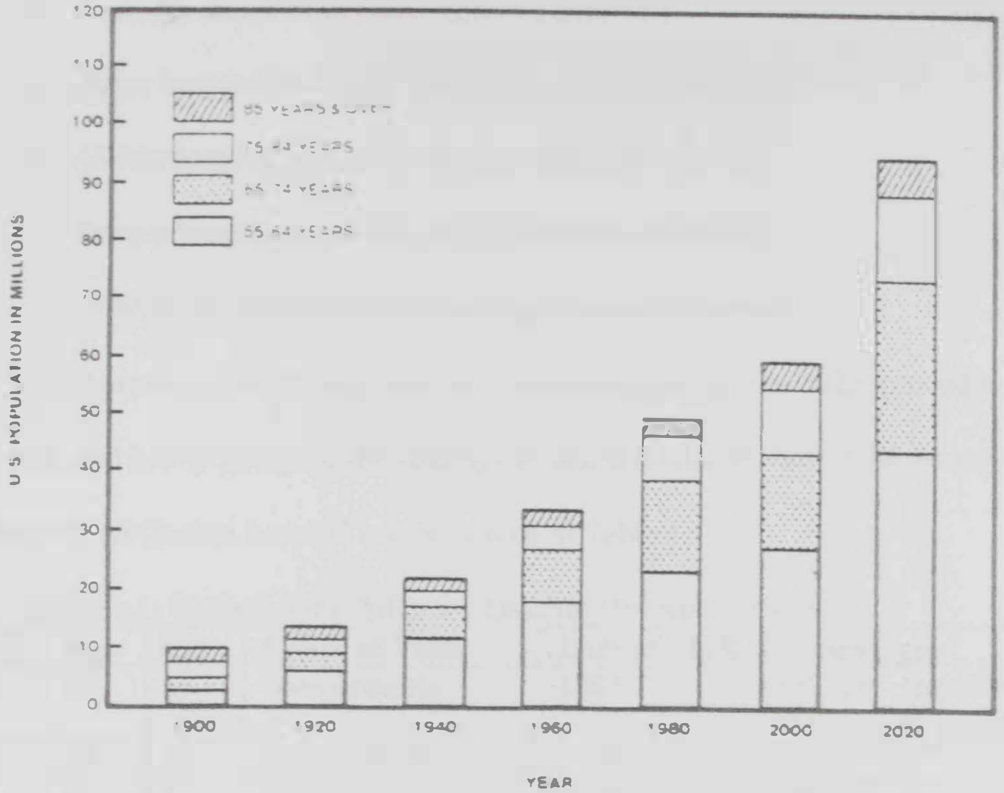

Figure 1.2: Population growth of individuals 55 years and over between the years 1900-2020 [3].

1.3 Research Motivation:

Statistics on THR procedures in the U.A.E. were conducted and covered most government and private hospitals that perform THR procedures through out the Emirates. These hospitals are:

1. Al-Qasimi hospital in Sharjah (government hospital)
2. Dubai hospital in Dubai (government hospital)
3. American hospital in Dubai (private hospital)
4. Sager hospital in Ras Al-khaima (government hospital)
5. Al-Ain hospital in Al-Ain city (government hospital)
6. Tawam hospital in Al-Ain city (government hospital)
7. Al-Mafrq hospital in Abu Dhabi (government hospital)

The purpose of this study was to understand, survey the THR procedures in the U.A.E. and hen to compare the findings to international studies. One example of this study for Al-Qasimi hospital is represented in Table 1.1.

Table 1.1: Statistic for (THR)- Al-Qassimi Hospital- Sharjah

NO	Age	Sex	Cause of THR	Date of THR	Follow-up
1	63	M	Osteoarthritis	1993	OK-no infection-no metal fatigue- no loosening
2	52	M	Osteoarthritis	2001	OK
3	77	F	Fracture	2002	OK
4	25	M	Fracture	2002	OK
5	28	F	Avascular necrosis (A.N)	2001	OK
6	37	F	Fracture	2001	OK
7	26	F	Avascular necrosis	2001	OK
8	57	F	Loosening of previous THR	2002	OK
9	44	M	Avascular necrosis	2001	OK
10	21	F	Avascular necrosis (Bilateral)	2001	OK

For the complete results, please refer to appendix B. The following observations can be drawn from the conducted field investigation:

- If we compare the number of the THR cases over years (Figure 1.3), we find that the years 2000 and 2001 have the highest number of THR cases performed (23 cases for both years).
- The number of THR cases is increasing since 1993 (the starting year in this study), except for the year 2002-2003. The reason for this decrease in the THR cases in this period is that the statistic covered only the first three to four months of the whole period.

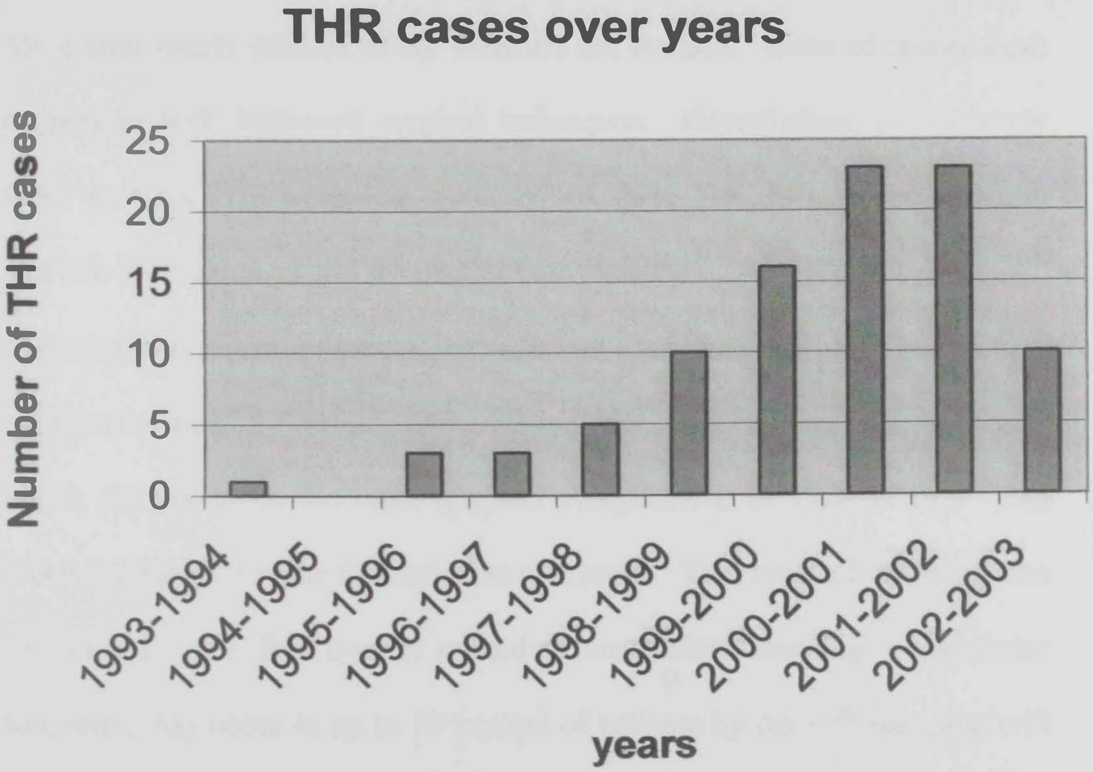

Figure 1.3: THR cases over certain years

- The age range for THR patients varies from 16 to 90 years. Patient age greater than 50 years represents fifty one percent of total candidates for THR. Meanwhile, patients between 30 and 50 years represent thirty five percent of total candidates for THR. More interesting is that the young patients' (who are less than 30 years) ages are increasing to represent thirteen percent of total candidates for THR. We found that our study agrees with the study found in reference [1].
- Fifty two percent of all THR procedures in this study are performed in men. Whereas forty eight percent of the THR procedures in this study are performed in women. The result differs slightly from the study found in reference [1].
- More than ninety percent of all THR are not revised. Rates of revision are decreasing with improved surgical techniques. Nevertheless, in our study there were six THR cases that were revised, three THR cases found infected, and two THR cases caused the death of the patient.
- Revision is a common factor associated with many late complications. There are many causes for revision. One of these causes is loosening of components, which merges to be the most frequent complication of THR [1,19]. This loosening may cause the femoral stem to fracture. Two types of loosening can be noticed. The first type is related to acetabular loosening. Acetabular loosening may occur in up to 10 percent of patients by the 10th year, and will probably increase in incidence with time. About one-half of these loose acetabular components are painful and may require revision surgery. The second type of loosening is related to femoral loosening. Loosening of femoral components is influenced by poor cementing techniques, varus

position, calcar resorption, inadequate prosthetic design, excessive patient weight and level of activity, and cement-layer fracture [1,20].

The second cause of loosening is infection. The infection rate is twice that for initial surgery. If infection occurs, it will cause medical complications such as progressive radiolucent lines. In general, if revision surgery is required because of infection, a satisfactory result is further jeopardized [1].

The incidence of loosening is much higher in younger patients. As a consequence of this loosening, revision surgery will be required in order to restore mobility and activities. So, the revision surgery in young patients will hinder them from their daily activities. In this situation, we have to search for a new material that will substitute, and offer superior advantages in contrast with the current materials used in THR.

In fact, the revision has negative impact on the patient side as well as the economic side. From the patient side, revision of THR is indicated when mechanical failure occurs. The surgery is technically more difficult and the long-term prognosis is generally not as good as for primary THR. The optimal surgical techniques for THR revision vary considerably depending on the conditions encountered. In conclusions, outcomes of revision hip surgery are less reliable and satisfactory than those of primary procedures. Those biologic, biomechanical, and rehabilitation factors that influence these results need to be explored and solutions developed. From economic side, the ultimate selection of THR system should be based on individualized patient needs, safety, and efficacy. Periodic follow up after THR procedure will allow identification of osteolysis and other indicators of impending failure in the earliest forms. As a consequence, this will save the patient from high cost of revising THR.

1.4 Objective of the thesis:

The main objective of the thesis is to investigate the performance of the braided composites for the design of a hip prosthesis made by a hybrid materials. To achieve the objective, the following criteria are considered:

- Selection of a new fiber reinforcement orientation, which is the braided technique.
- Selection of a new composite material, which is the hybrid composite.
- Mechanical performance will be evaluated to investigate the mechanical properties (i.e., strength and modulus) of different fiber-reinforced composite structures.
- Scanning- electron microscopy (SEM) will be used to evaluate the effects of the physiological solution on the mechanical properties of the tested samples.

1.5 Thesis outline:

The aim of this thesis is to investigate the performance of the braided composites for the design of a hip prosthesis made from hybrid materials. This thesis is divided into six chapters. Chapter 1 introduces the subject by briefly defining the total hip joint replacement (THR) concept with a background about the topic. The remaining of the chapter covers the research motivation and the objective of the thesis.

Chapter 2 reviews the relevant literature on the total hip joint replacement (THR). It also introduces several issues like drawbacks of metal alloys, composite stems and surveys of current developments of composite stems. Chapter 3 describes the design components of the hip prosthesis, which includes the fibers and the resin.

It also covers the design calculations and theoretical calculations. Chapter 4 presents the processing techniques that were used to manufacture the samples. It also includes the experimental testing that was done for the specimens. Chapter 5 addresses the discussion of the results found in this study. Finally, general conclusions and recommendations will be drawn in Chapter Six.

Chapter 2

Literature Review

2.I Introduction:

The use of materials for replacing or strengthening the human skeletal system dates back as far as 3000 BC when bronze was first used be the Egyptians in attempts for repair skull injuries. Few advances emerged in orthopedics when orthopedic surgeons discovered that bone fracture fixation could improve recovery. In the early materials discovery, metals were used to repair bone fractures. Later on, it was discovered that metals have a higher stiffness than bone, which can cause loosening.

The hip prosthesis was the first popular permanent implant device, when total hip replacement (THR) became a routine procedure in the early 1960s with important developments. The advancements that occurred to the hip prosthesis were similar to the advancements for bone fracture fixation. In other words, metals were first used in the hip prosthesis design. The advances in the artificial hip joint prosthesis materials have been also going through tremendous developments in the past years. This chapter will review these advances with emphasis being given to the recent trends in the artificial hip prosthesis design.

2.2 Historical development of hip arthroplasty:

The word ‘arthroplasty’ means ‘to make or refashion a joint’. The simplest form of arthroplasty is excision arthroplasty (Figure 2.1). The type of surgery is still carried out extensively by orthopedic surgeons. It involves the excision of one or both of the bony articular surfaces of a joint, leading to the formation of a new or false joint-that is, a pseudarthrosis. In the hip joint this involves removing the head of the femur and not replacing it with any prosthetic material at all. This is known as a Girdlestone's arthroplasty [18].

Figure 2.1: Excision arthroplasty. One or both of the bony articular surfaces are excised, leading to the formation of a new of false joint [18].

The next form of arthroplasty is interposition arthroplasty, in which some material is 'interposed' or placed between the diseased articular surfaces (Figure 2.2). The material may be biological, such as autologous skin, muscle or fascia-or it may be prosthetic. Biological interposition arthroplasties were used in the treatment of hip joint disease as early as 1880 in France by Ollier, who used muscle tissue, and by others in the early 1900s using fascia or the chromicised submucosa of a pig's bladder [18].

Figure 2.2: Interposition arthoplasty. Biological or prosthetic material is placed between the articular surface [18].

Interposition hip arthroplasty using gold foil was performed by Robert Jones in 1895. However, interposition arthroplasty using prosthetic materials did not become a widely used technique until Smith Peterson in Boston popularized the procedure, initially using a glass cup in 1928 and subsequently (after trying Pyrex and Bakelite) using vitallium (cobalt-chrome alloy) in the late 1930s. This became a very popular procedure for the treatment of hip arthritis for the next 30 years and was known as the Smith Peterson Cup arthroplasty of the hip.

A more sophisticated form of arthroplasty was then developed-the partial replacement arthroplasty (Figure 2.3), in which the head of the femur is removed and replaced with a prosthetic femoral head. This technique was pioneered by Wiles in Britain, Thomson in the USA and the Judet brothers (who used acrylic prostheses) in France. The Moore's prosthesis, developed in the USA in the 1950s, is still used today in partial replacement arthroplasty in elderly patients who have sustained a displaced subcapital fracture of the neck of the femur [18].

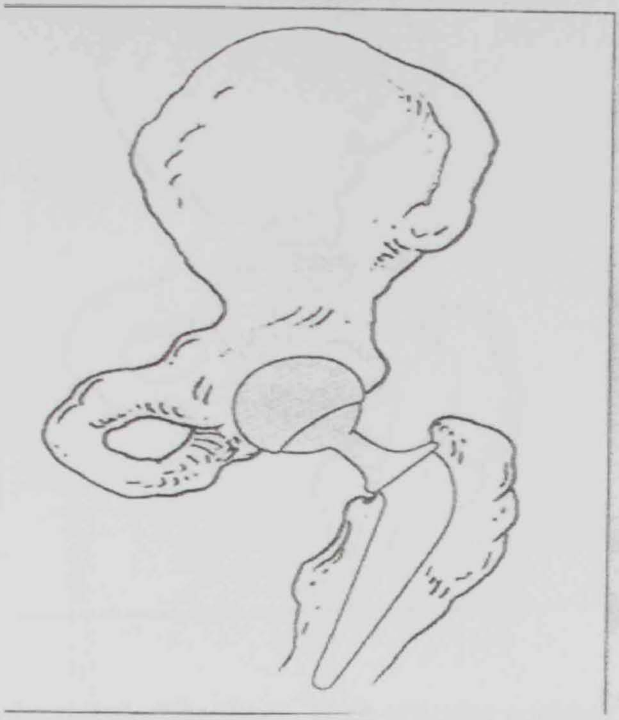

Figure 2.3: Partial replacement arthroplasty. The head of the femur is removed and replaced with a prosthesis [18].

Finally, because none of the earlier prostheses was entirely satisfactory, there was the inevitable development of the total replacement arthroplasty (Figure 2.4), in which both articular surfaces are replaced with prosthetic materials. McKee in Britain in the 1950s was one of the first to popularize a metal-on-metal articulation. He initially used screws to fix the metal to the bone, but later used methyl methacrylate (cement), as popularized by Sir John Charnley.

Figure 2.4: Total replacement arthoplasty. Both articular surfaces are replaced with prosthesis [18].

A significant contribution was made by Sir John Charnley who set up the famous center for hip surgery in Wrightington, near Wigan in northern England. Charnley recognized the importance of low friction for the bearing surfaces and, as a result, designed the famous small femoral head (22.25 mm). Initially he used Teflon or Fluon acetabular cups, but these were found to wear rapidly and produce large amounts of wear debris. The debris caused a major biological reaction to occur around the prosthesis, resulting in osteolysis and, ultimately, loosening of the prosthesis (Figure 2.5)[22].

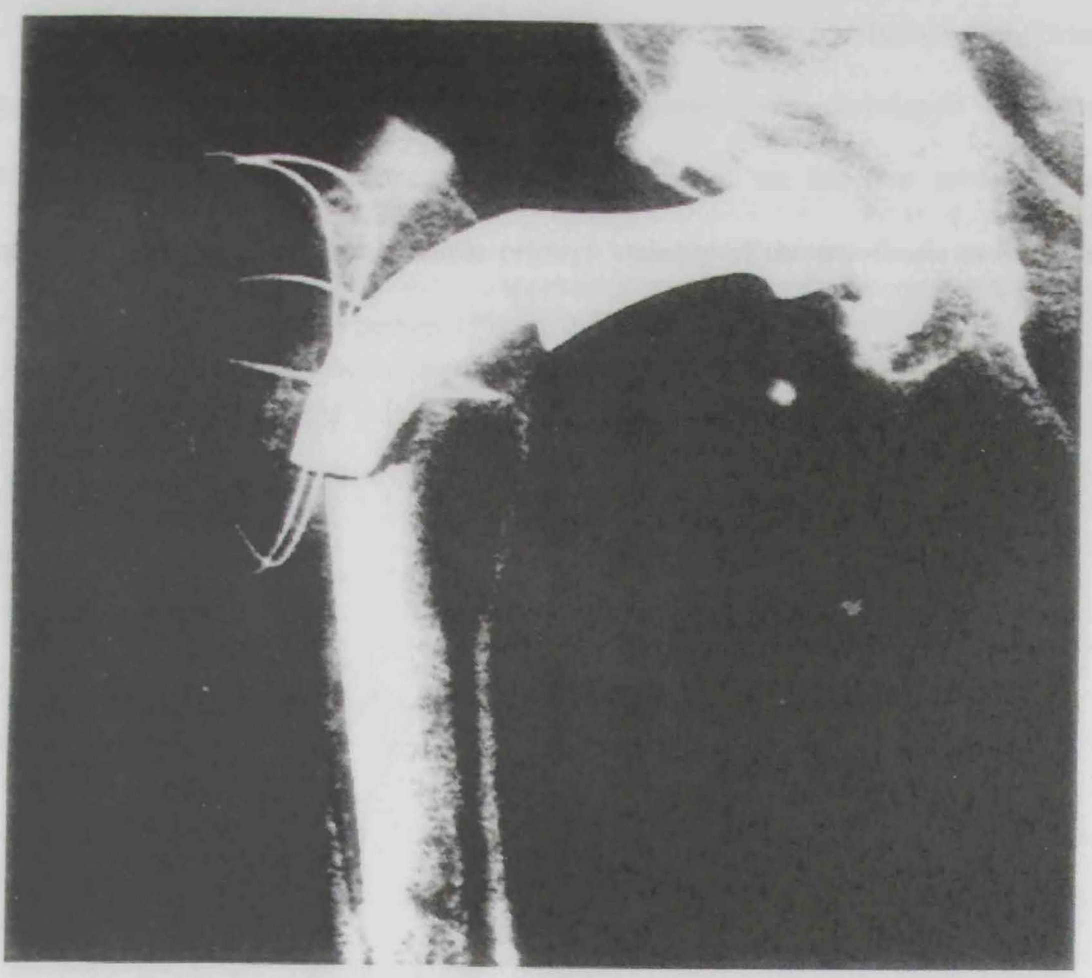

Figure 2.5: X-ray showing fatigue breakage of a Charnley-type femoral prosthesis [3].

Charnley made three major contributions to the science of hip arthroplasty surgery. First, he demonstrated that polyethylene (in particular, Ultra high molecular weight polyethylene-UHMWPE) was a suitable bearing surface for low friction arthroplasty. Secondly, he recognized the importance of methyl methacrylate (calculated molecular weight cement) as an inert grouting substance for the fixation of the prosthesis to the bone. Thirdly, he was able to reduce the infection rate following the procedure (from 7% to less than 1%) by using an ultraclean operating room, laminar airflow and personal isolation exhaust systems.

These developments open the door for new designs and materials, and during the next 25 years, a variety of artificial hip joints were developed by many orthopaedic surgeons in Europe and the USA, based on the two principles of Charnley: low friction and immediate primary stability of the prosthesis in the bone by anchoring it with acrylate cement (Figure 2.6).

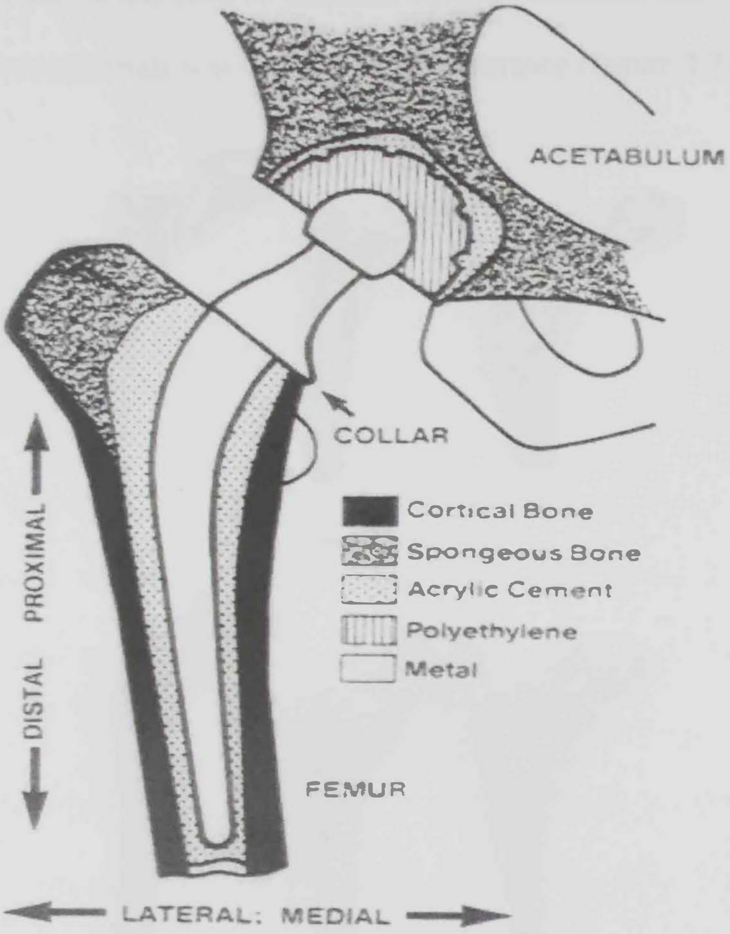

Figure 2.6: First THR technique. Cemented fixation method, where the prosthesis is anchored in the bone with acrylate cement [3].

The growing demand of cement-free hip prostheses in the course of the 1970s and 1980s was motivated partly by unsatisfactory results with cement anchorages that were not always optimal. However, a hip prosthesis anchored in the bone without the use of bone cement demands an even more careful surgical technique than when using components with bone cement. In the design, special attention must be given to the immediate primary stability of the socket and stem [2].

Semlitch [2] reviewed the developments made with artificial hip joints materials during the last twenty years. Actually, his review is not up-to-date, but covers all achievements done in metal implants. As it may be anticipated, early developments consider metals such as titanium, cobalt, vanadium, and one important requirement for these materials was their corrosion resistance (Figure 2.7).

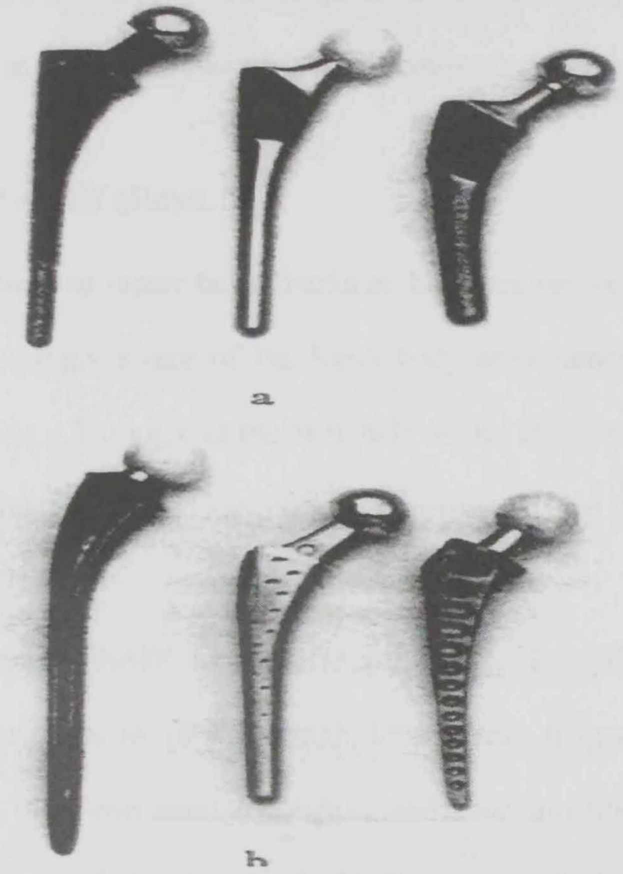

Figure 2.7: Various (a) porous coated and (b) uncoated press fit-typed total hip replacement. Most include a modular ceramic or metal head [3]

When replacing a painful deformed hip joint, the following objectives are aimed at, through the optimal choice of implant design and materials:

1. Painless joint movement with low friction, that is ball-and socket materials with low coefficient of friction;

2. Little wear sustained by the artificial joint, that is ball-and-socket materials with high wear resistance;
3. High corrosion resistance in all materials used;
4. Good biocompatibility of all implanted materials;
5. High mechanical strength in the stressed materials of achoring stems, especially under bending and torsion;
6. Stable primary anchorage of prosthesis components in the acetabulum (socket) and femur (thigh bone) to prevent subsequent loosening;
7. Salvage facility in case the implant has to be removed.

2.3 Drawbacks of metal alloys:

Initially, metals were used to repair bone fractures, but over the years, orthopaedic surgeons became increasingly aware of the harsh body environment and complex loading on the prosthesis. Throughout the first half of the 20-century, the primary concern of metal implant materials was corrosion resistance and biocompatibility within the body [3].

Titanium alloys such as TiAlV and TiAlNb are commonly used as the material for noncemented stems because of their high tensile and fatigue strength, low modulus of elasticity, high corrosion resistance, and biocompatibilty. However, blackening of the adjacent tissue commonly is observed with Ti alloy implants because of abrasive wear debris from bearing surfaces and mechanical instability of stems. This discoloration is accompanied by a typical macrophage response stimulating bone resorption and consequent osteolysis. Although CoCrMo alloys are much less prone to wear and corrosion than Ti alloys, substantial amounts of wear particles are generated in vivo [4] in metal on metal prostheses, especially during the initial running period [5].

The use of metal implants (Cobalt chromium alloy and titanium alloy prostheses) creates major problems. First, the stiffness of metallic prostheses is relatively high compared to the surrounding, load carrying bone. The elastic modulus for metallic implants is between 110 GPa for titanium alloy and 210 GPa for Cobalt chromium alloy or steel whereby the elastic modulus of cortical bone varies from 15 to 25 GPa. Therefore, the prosthesis assumes the major amount of the load originally carried by the bone. The long-term response of the human body is resorbing the unloaded bone material. This may cause the degradation of the bone implant interface, forming gaps between the prosthesis and the remaining bone and may cause the stem to loosen. The second disadvantage of metallic prostheses is that patients may experience hypersensitivity as a result of release of metallic ions caused by corrosion or enzymatic effects or particles caused by wear [25].

Although total hip replacement has been successful over the last 30 years, complications of loosening and resorption of the calcar still exist. This confines the application to elderly patients. It is widely accepted that the reason for the calcar resorption is the mechanical mismatch between the bone and the implant material. Current metallic implants have stiffness of at least five to six times that of bone. The load carried by the intact femur before the operation is shared with the stem after the operation. Most of the load is carried by the implant due to its greater stiffness. Thus bone starts to resorb in order to adapt to itself to this newly created stress distribution in the calcar [6].

The proposed solution to this complication is to use a less stiff material with mechanical properties close to the properties of bone (i.e., "iso-elastic" materials).

The strength and stiffness of composite materials can be tailored very easily as compared to metals. For example, the elastic modulus can range from 1 to 170 GPa (strength from 70 to 1,900 MPa) for a PEEK or PS matrix reinforced with carbon fibers. The following section discuss the opportunities offered by composite materials and review some of recent research work performed to investigate the opportunity of considering these materials for the design of the hip joint.

Also the use of composite materials in orthopaedic surgery offers a variety of new implant designs. Outstanding mechanical properties; radiolucency, biocompatibility and low weight are the major advantages compared with metals in clinical use today.

2.4 Composite stems

All research initiative focused on the design of the stem rather the complete hip joint [7]. Since existing problems with metals hip joints were attributed mainly to the stem. The use of composite materials allows the designer to tailor the mechanical properties such as the elastic moduli to match that of bone to provide a state of stress in the femur closer to physiological level when compared to metal implants. The mechanical properties can be tailored to the patients' age, size and activity level. A further advantage of composite material is their enhanced damage tolerance and fatigue and corrosion resistance. Carbon has been shown to be inert to harsh body environment and it appears to be superior to other materials used for implant applications to date [7].

Due to the direct contact between the bone and prosthesis surfaces, stress shielding is another issue in orthopaedic application. The stem 'shields' the bone from stress because it shares the load that is normally taken by the bone alone. It has been demonstrated that implants with lower elastic moduli can reduce the effect of stress shielding around the proximal region of the femur. Since the elastic moduli of currently used prosthesis materials such as cobalt-chrome and titanium alloy are significantly higher than bone, they show different degrees of stress shielding of bone [8,9]. Stress shielding is caused by the non-physiological manner of joint-to-bone transfer and is proportional to the structural stiffness of the femoral component. Low-stiffness composite implants have been shown to reduce stress shielding. However, clinical experience has shown that the strength of such stems is a serious concern that provides a challenge to implant designers. In a laminated stem, the designer has the freedom to vary the orientation of each ply to achieve beneficial stiffness, stress distributions, subsequent component strength, and physiological performance [10,21,23].

2.5 Survey of current development of composite stems

The first developed composite stem was designed using short carbon fiber reinforced with a thermoplastic matrix (PEEK). This composite material has mechanical properties suitable for the orthopaedic application. The reported modulus of elasticity (13- 20 GPa, depending on the processing conditions, fiber orientation, and length distribution) is similar to the bone modulus of elasticity (17.6 GPa). It is known to be resistant to many chemical solutions, and some studies have shown that it is also biocompatible [6]. When compared to their metal counterpart (Ti-6Al-4V), the following was observed:

1. Finite element models are in good agreement with the results of experimental strain gauge measurement except for the hoop stresses in cortical bone. This may be due to the assumption of isotropic material properties for the artificial femur, which is not the case in real bone.

2. Stem stresses are lower for the CF/PEEK prosthesis compared with titanium prosthesis. The maximum stress in the composite prosthesis occurs in the spigot, whereas it occurs in the middle third of the titanium stem.
3. The cement stresses are almost equal for both prostheses although more load is transferred along the stem length with the CF/PEEK prosthesis because the load transfer takes place over a larger area with the composite prosthesis. However, higher stresses are observed in the cement layer trapped between the collar of CF/PEEK prosthesis and the neck of the femur [6].
4. An out-of-plane component of the joint load causes higher prosthesis and cement stresses. This outlines the importance of the material properties on the accurate estimation of the bone stresses. Thus, for design purposes, the hip joint load must be a three-dimensional load that accounts for the out-of-plane load component. The magnitude of the loads must be known accurately for various activities because out-of plane component play an important role, particularly in running and stair climbing, in the critical stresses of the components.

The second composite material system to be selected was a thermoplastic unidirectional graphite/PEEK [8,9]. An investigation was performed to study the mechanical performance of fiber-reinforced composite hip joint prosthesis in a femur. The main objective of the study was to evaluate the effect of fiber orientation of a composite femoral implant on the response of the surrounding femoral bone. A three dimensional finite element analysis was deveoped for analyzing a composite implant in the femur. Based on the analysis, it was shown that more favorable stresses and deformations could be generated in the femur using composite implants compared to conventional metallic implants. In addition, by changing fiber orientations compared to femoral loads, a composite implant could be designed specifically for the left or the right femur. The model has demonstrated that the initial fixation is critical for the use of composite implants because lower moduli produce higher implant deformations. The long-term stability of composite implants seems to be very promising as the modeling conducted in this research program predicts that more favorable stresses and deformations could be produced in the femur using composites than be obtained with metallic based stem designs. However, caution must be exercised with regard to the results of the calculations. Different shapes and loading conditions may affect the results of the calculations. In addition, the effect of composite on biological bone remodeling was not considered.

The third material system to be selected was a carbon fiber-reinforced epoxy. In this study, the objective was to investigate failure loads and critical stresses of an anatomically shaped carbon fiber hip stem [13]. Implants were manufactured by two methods. One it to mill the structure out of thick, multi-ply laminates. The other method is a filament winding process using oriented continuous fibers. The FEM analysis has shown that the fracture was located at the antero-medial aspect (right femur) above the resection plane stimulating a well-ingrown endoprothesis. The calculated fracture load of 11.9 KN corresponds again with the experimental values and exceeds the strength determined according to ISO testing. Therefore, the risk of implant failure due to unconsidered failure modes can be excluded for the structure observed. Owing to the excellent correlation between the FEM results and the experimental values, the design of carbon fiber implants can be achieved by computer stimulation prior to time and cost intensive prototype manufacturing.

Using the same material system, Kuo and Perez [13] studied how the stiffness and strength of composite hip prosthesis can be affected by variations in ply orientations and stacking sequence for a selected manufacturing method. This investigation involved both analytical and experimental work. It was found that an optimal design of hip stems can be achieved by using advanced fiber reinforced composite materials, but great care must be taken when selecting the appropriate ply orientation and stacking sequence (lamination) for a chosen fabrication method. The loading condition (in-plane and out-of-plane angles) significantly affects the strength and failure mode of composite stems.

The fourth material system used was a carbon-carbon composite [14]. This composite was made of carbon fibers infiltrated either with dense pyrolitic carbon or silicon carbide (SiC) through chemical vapor infiltration. The chemicophysical properties of these composites are examined according to their structures. The long-term response (2 years) of cortical bone to various types of carbon-carbon was evaluated mainly for bone contact and ingrowth. Carbon-carbon coated with calcium phosphate was found to speed up the bone formation as compared to pyrolitic carbon or SiC coatings. The low modulus of elasticity of the C-C materials could be responsible for quicker bone contact as compared to a much stiffer material like sintered aluminum oxide. The biomechanical performance of C-C hip stems was assessed through (a) implantation into cadaver femurs, (b) fatigue testing, and (c) finite element analysis. These tests showed: (a) a better stress transfer as compared to a metal prosthesis having the same design, (b) no fatigue damage, (c) a computerized stem stress distribution in accordance with the fractures obtained during static mechanical testing.

The fifth material system used was a braided composite. The objective of this work was to analyze the strength and stiffness properties of braided composites impregnated with epoxy resin. The paper reviewed the research and developments that have been going on to improve the hip prosthesis manufacturing and design. The paper justified the reasons behind using braided composites in the hip prosthesis. The reasons are due to the high mechanical performance and low manufacturing cost. In this work, six tabular specimens, three of glass and three of hybrid glass-carbon fiber reinforcement, were manufactured using compression molding technique. For the purpose of designing, structural stiffness was controlled in two ways. The first way was to vary continuously the modulus along the prosthesis length or by combining two, or more materials, different modulus to achieve the required stiffness. For the time being, this technique is still theoretical due to the difficulty of manufacturing a device with such a highly differentiated modulus. The second solution for controlling the stiffness was to vary the relative thickness of the composite layers. In this study, the second solution was adopted due to its simplicity and possibility to implement. The elastic constants were measured for the two braided composites. The results showed that both of the structures possess similar axial and circumferential Young's modulus and Poisson's ratios. The similarity is due to the fiber type and modulus. Glass fiber showed higher volume fibers (around 20%) due to the effectiveness of impregnation process. On the other hand, carbon fibers have been added to the braided glass to increase its strength. In conclusion, braiding technique is very good solution to improve the quality of the composite hip prosthesis [24].

It is clear that despite promising results obtained with composite stems, further investigation is needed to explore to benefits offered by composite materials. Actually, most research focused on unidirectional composites made from carbon fibers and epoxy matrix. However, it is known that laminates made from unidirectional reinforcement will experience delamination and offers less fatigue resistance. For that reason, we plan to investigate the performance of braided composite. Braided fabrics are known for their high mechanical performance, especially their high resistance to delamination. Furthermore in order to reduce the cost of these implants, we plan to investigate the use of hybrid materials. These materials will combine the properties of each constituent. For example, a hybrid material made from carbon and aramid will features the high strength of carbon fibers in addition to high impact resistance of aramid fibers [16,24].

Chapter Three

Material selection and design

3.1 Materials description:

3.1.1 Matrix:

The role of the matrix in a fiber-reinforced composite is (1) to transfer stresses between the fibers, (2) to provide a barrier against an adverse environment, and (3) to protect the surface of the fibers from mechanical abrasion. The matrix plays a minor role in the tensile load-carrying capacity of a composite structure. However, a selection of a matrix has a major influence on the interlaminar shear as well as in plane-shear properties of the composite material. The interlaminar shear strength is an important design consideration for structures under bending load, whereas the in-plane shear strength is important under torsional loads. The matrix provides lateral support against the possibility of fiber buckling under compression loading, thus influencing to some extent the compressive strength of the composite material. The interaction between fibers and matrix is also important in designing damage-tolerant structures. Finally, the processability and defects in a composite material depend strongly on the physical and thermal characteristics, such as viscosity, melting point, and curing temperature of the matrix.

Table 3.1 lists various matrix materials that have been used either commercially or in research. One family of these matrix materials is thermoplastic polymers, such as nylon, polyesters, polycarbonate, polyamide imide, polyether-ether ketone (PEEK), and polysulfone. Another matrix material is thermoset polymers, such as epoxies, polyester, vinlyesters, phenolics, and polyimides. In addition to these two families, other matrix materials such as ceramic and metallic matrices are available.

Table 3.1: Matrix materials

Polymeric

- Thermoset polymers (resins)
  - Epoxies: principally used in aerospace and aircraft applications.
  - Polyester, vinyl esters: commonly used in automotive, marine, chemical, and electrical applications.
  - Phenolics: used in bulk molding compounds.
  - Polymidides, polybenzimidazoles (PBI), polyphenylquinoxaline (PRQ): for high-temperature aerospace applications (temperature range: 250-400 °C).
- Thermoplastic polymers
  - Nylons (such as nylon 6, nylon 6,6), thermoplastic polyesters (such as PET, PBT), polycarbonate (PC), polyacetals: used with discontinuous fibers in injection-molded articles.
  - Polyamide-imide (PAI), polyether-ether ketone (PEEK), polysulfone (PSUL), polyphenylene sulfide (PPS), polyether imide (PEI): suitable for moderately high temperature applications with continuous fibers.

Metallic

- Aluminum and its alloys, titanium alloys, magnesium alloys, copper-based alloys, nickel-based superalloys, stainless steel: suitable for high-temperature applications (temperature range: 300-500 °C).

Ceramic

- Aluminum oxide (Al_2O_3), carbon, silicon carbide (SiC), silicon nitride (Si_2N_4): suitable for high-temperature applications.

3.1.1.1 Thermoplastic and thermoset polymers:

Polymers are divided into two broad categories: thermoplastics and thermosets. In a thermosplastic polymer, individual molecules are linear in structure with no chemical linking between them (Figure 3.1a). They are held in place by weak secondary bonds (intermolecular forces), such as van der Waals bonds and hydrogen bonds. With the application of heat and pressure, these intermolecular bonds in a solid thermoplastic polymer can be temporarily broken, and the molecules can be moved relative to each other to flow into new positions. Upon cooling, the molecules freeze in their positions, resorting the secondary bonds between them and resulting in a new solid shape. Thus, a thermoplastic polymer can be softened, melted, and reshaped (post formed) as many times as required.

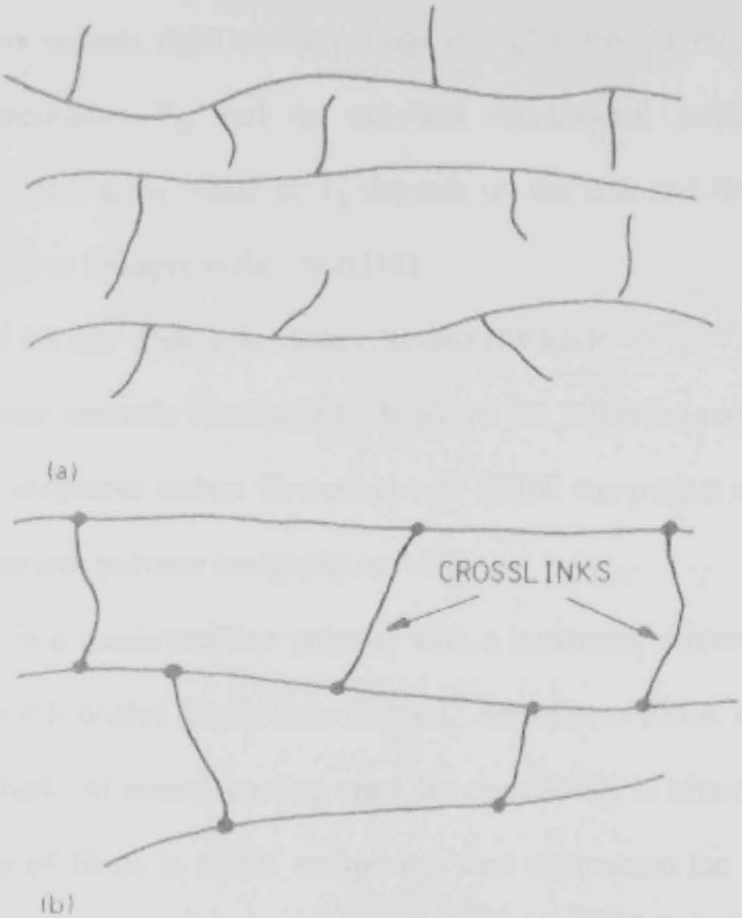

Figure 3.1: Schematic representation of (a) thermoplastic and (b) thermosetting polymers [15].

In a thermoset polymer, on the other hand, the molecules are chemically joined together by cross-links, forming a rigid, three-dimensional network structure (Figure 3.1b). Once these cross-links are formed during the polymerization reaction (also called the curing reaction), the thermoset polymer cannot be melted and reshaped (postformed) by the application of heat and pressure. However, if the number (frequency) of cross-links is low, it may still be possible to soften them at elevated temperatures [15] .

3.1.1.1.1. Thermoplastic matrix:

Table 3.2 lists the mechanical properties of selected thermoplastic polymers that are considered suitable for high-performance composite applications. The molecules in these polymers contain rigid aromatic rings that give them a relatively high-class transition temperature T_g, and an excellent dimensional stability at elevated temperatures. The actual value of T_g depends on the size and flexibility of other chemical groups or linkages in the chain [15].

3.1.1.1.1.1 Poly ether Ether Ketone (PEEK):

PEEK is a linear aromatic thermoplastic based on the following repeating unit in its molecules. Continuous carbon fiber-reinforced PEEK composites are known in the industry as aromatic polymer composite or APC.

PEEK is a semicrystalline polymer with a maximum achievable crystallinity of 48 % when it is cooled slowly from its melt. Amorphous PEEK is produced if the melt is quenched. At normal cooling rates, the crystallinity is between 30 and 35 %. The presences of fibers in PEEK composites tend to increase the crystallinity to a higher level, since the fibers act as nucleation sites for crystal formation. Increasing crystallinity increases both modulus and yield strength of PEEK, but reduces its strain-to-failure (Figure 3.2).

PEEK has a glass transition temperature of 143 ^{o}C and a crystalline melting point of 335 ^{o}C. Melt processing of PEEK requires a temperature range of 370-400^{o}C. The maximum continuous use temperature is 250^{o}C.

PEEK is the foremost thermoplastic matrix that may replace epoxies in many aerospace composites. The outstanding property of PEEK is its high fracture toughness, which is 50-100 times higher than epoxies. Another important advantage of PEEK is its low water absorption, which is less than 0.5 % at 23 °C compared to 4-5 % for conventional aerospace epoxies. Being semicrystalline, it does not dissolve in common solvents. However, it may absorb some of these solvents, most notably methylene chloride. The amount of solvent absorbed decreases with increasing crystallinity [15].

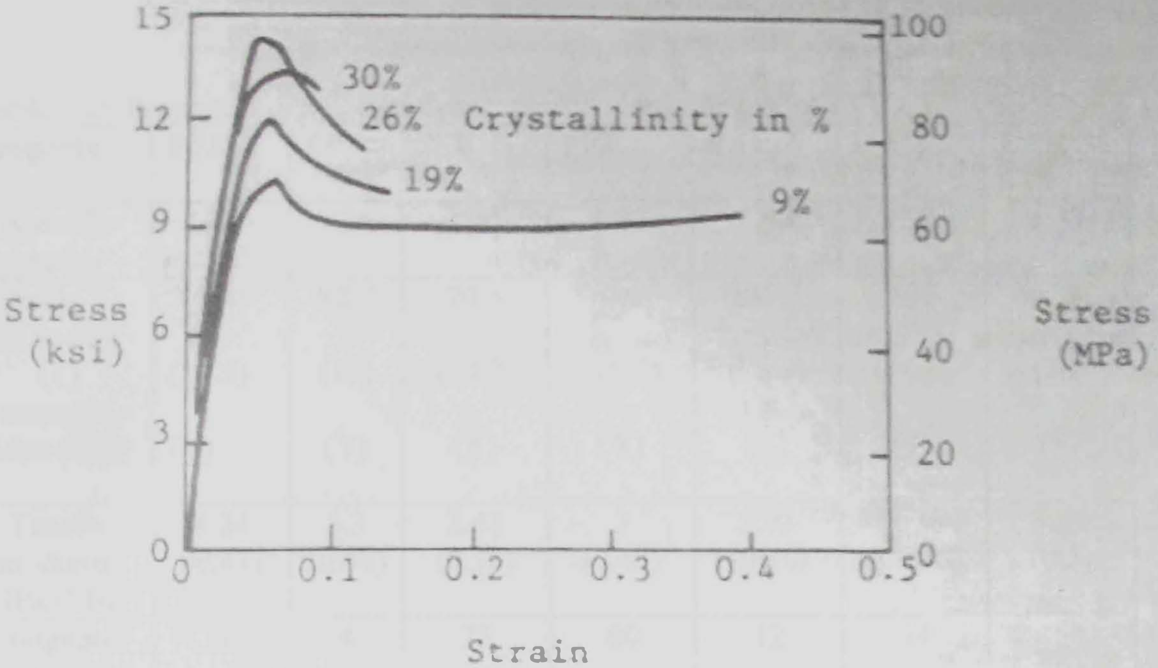

Figure 3.2: Tensile stress-strain diagrams of PEEK at different crystallinities [15].

Table 3.2: Properties of selected thermoplastic matrix resins (at 23^{o}C)

property	**PEEK**	**PPS**	**PSUL**	**PEI**	**PAI**	**K-III**	**LARC-TPI**
Specific gravity	1.30-1.32	1.36	1.24	1.27	1.40	1.31	1.37
Yield (Y) or tensile (T) strength, Mpa (Ksi)	100 (14.5) (Y)	82.7 (12) (Y)	70.3 (10.2) (Y)	105 (15.2) (Y)	185.5 (26.9) (T)	102 (14.8) (T)	138 (20) (T)
Tensile modulus, GPa (Msi)	3.24 (0.47)	3.3 (0.48)	2.48 (0.36)	3 (0.43)	3.03 (0.44)	3.76 (0.545)	3.45 (0.5)
Elongation-at- break (%)	50	4	75	60	12	14	5
Poisson's ratio	0.4	_	0.37	_	_	0.365	0.36
Flexural strength, MPa (Ksi)	170 (24.65)	152 (22)	106.2 (15.4)	150 (21.75)	212 (30.7)	_ _	_ _
Flexural modulus, GPa (Msi)	4.1 (0.594)	3.45 (0.5)	2.69 (0.39)	3.3 0.48)	4.55 (0.66)	_ _	_ _
Fracture energy, G_{Ic},KJ/m^2	6.6	_	3.4	3.7	3.9	1.9	_
HDT, ^{o}C (ar 1.82 MPa)	160	135	174	200	274	_	_
Coefficient of thermal expansion, $10^{-5}/^{o}C$	4.7	4.9	5.6	5.6	3.6	_	3.5

3.1.1.1.2 Thermoset matrix:

3.1.1.1.2.1 Epoxy:

The starting materials for epoxy matrix are low-molecular -weight organic liquid resins containing a number of epoxide groups, which are three-membered rings of one oxygen atom and two carbon atoms. A common starting material is diglycidyl ether of bisphenol A (DGEBA), which contains two epoxide groups, one at each end of the molecule (Figure 3.3a). Other ingredients that may be mixed with the starting liquid are diluents to reduce its viscosity and flexibilizers to improve the impact strength of the cured epoxy matrix [15].

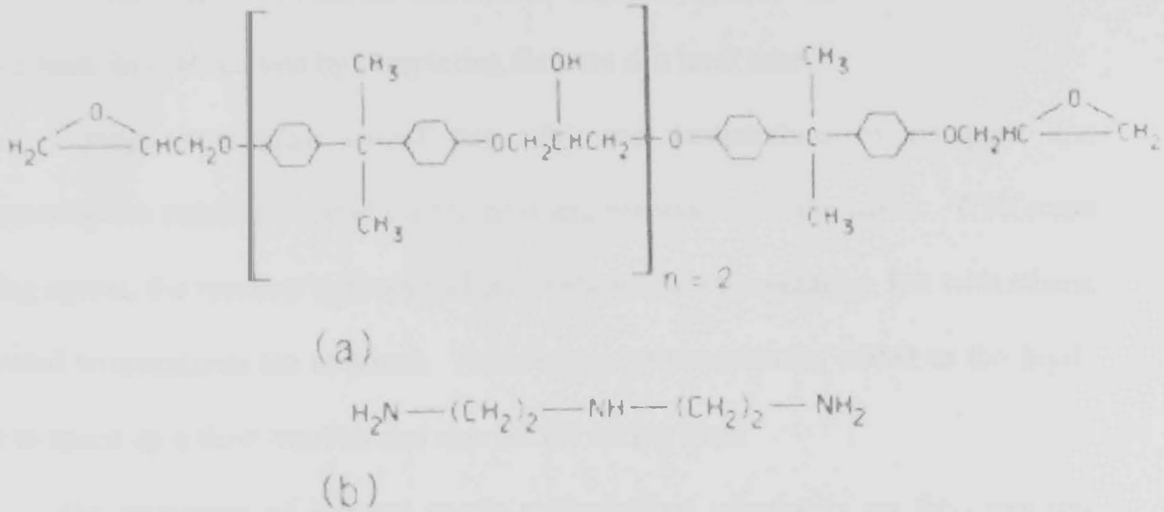

Figure 3.3: Principal ingredients in the preparation of an epoxy matrix. (a) A molecule of diglycidyl ether of bisphenol A (DGEBA) epoxy resin. (b) A molecule of diglycidyl triamine (DETA) curing agent [15].

The polymerization (curing) reaction to transform liquid resin to the solid state is initiated by adding small amounts of a reactive curing agent just prior to incorporating fibers into the liquid mix. One such curing is diethylenetriamine (DETA, Figure 3.3b). Hydrogen atoms in the amine (NH_2) groups of a DETA molecule react with the epoxide groups of DGEBA molecules in the manner illustrated in Figure 2.4a. As the reaction continues, DGEBA molecules form cross-links with each other (Figure 3.4b) and a three-dimensional network structure is slowly formed (Figure 3.4c). The resulting material is a solid epoxy resin [15].

If the curing reaction was slowed by external means (e.g., by lowering the reaction temperature) before all the molecules are cross-linked, the resin would be in B-stage form. At this stage, cross-links have formed at widely spaced points in the reactive mass. Hardness, tackiness, and the solvent reactivity of the B-staged resin depend on the degree of cure advancement. The B-staged resin can be transformed into a hard, insoluble mass by completing the cure at a later time.

Curing time (also called pot life) and temperature to complete the polymerization reaction depend on the type and amount of curing agent. With some curing agents, the reaction initiates and proceeds at room temperature, but with others, elevated temperatures are required. Accelerators are sometimes added to the liquid mix to speed up a slow reaction and shorten the curing time.

The properties of a cured epoxy resin depend principally on the cross-link density (spacing between successive cross-link sites). In general, the tensile modulus, glass transition temperature, and thermal stability as well as chemical resistance are improved with increasing cross-link density, but the strain-to-failure and fracture toughness are reduced. Factors that control the cross-link density are the chemical structure of the starting liquid resin (e.g., number of epoxide groups per molecule and spacing between epoxide groups), functionality of the curing agent (e.g., number of active hydrogen atoms in DETA), and the reaction conditions, such as temperature and time [15].

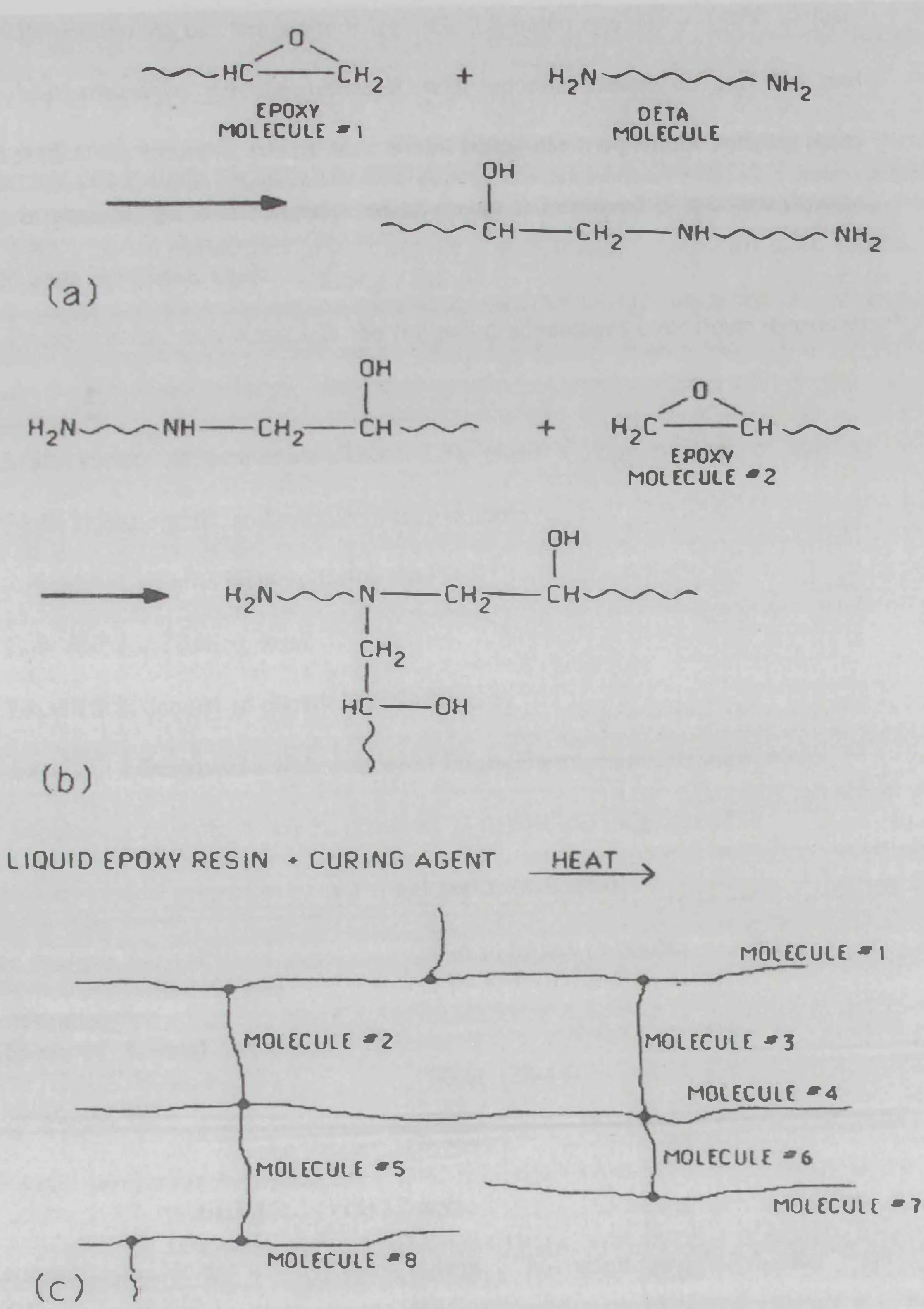

Figure 3.4: Schematic representation of a cross-linked epoxy resin. (a) Reaction of epoxide group with DETA molecule; (b) formation of cross-links; (c) three-dimensional network structure of solid epoxy [15].

The continuous use temperature for DGEBA-based epoxies is 150°C or less. Higher heat resistance can be obtained with epoxies based on novolac and cycloaliphatics, for example, which have a continuous use temperature ranging up to 250°C. In general, the heat resistance of an epoxy is improved if it contains more aromatic rings in its basic chain.

Epoxy matrix, as a class, has the following advantages over other thermoset matrices:

1. Wide variety of properties (Table 3.3), since a large number of starting materials, curing agents, and modifiers are available.
2. Absence of volatile matters during cure
3. Low shrinkage during cure
4. Excellent resistance to chemicals and solvents
5. Excellent adhesion to a wide variety of fillers, fibers, and other substrates

The principal disadvantages are its relatively high cost and long cure time.

Table 3.3: Typical properties of cast epoxy resins (at 23 °C)

Specific gravity	1.2-1.3
Tensile strength, MPa (Psi)	55-130 (8000-19,000)
Tensile modulus, GPa (10^6 psi)	2.75-4.10 (0.4-0.595)
Poisson's ratio	0.2-0.33
Coefficient of thermal expansion, 10^{-6} m/m per °C (10^{-6} in./in. per °F)	50-80 (28-44)
Cure shrinkage, %	1-5

3.1.1.1.2.2- Vinyl Ester:

The starting material for a vinyl ester matrix is an unsaturated vinyl ester resin produced by the reaction of an unsaturated carboxylic acid, such as methacrylic or acrylic acid, and an epoxy resin (Figure 3.5). The C = C double bonds (unsaturation point) occur only at the ends of a vinyl ester molecule, and therefore, cross-linking can take place only at the ends, as shown schematically in Figure 3.6. Because of fewer cross-links, a cured vinyl ester resin is more flexible and has higher fracture toughness than a cured polyester resin. Another unique characteristic of a vinyl ester molecule is that it contains a number of OH (hydroxyl) groups along its length. These OH groups can form physical (hydrogen) bonds with similar groups on a glass fiber surface resulting in excellent wet out and good adhesion with glass fibers [15].

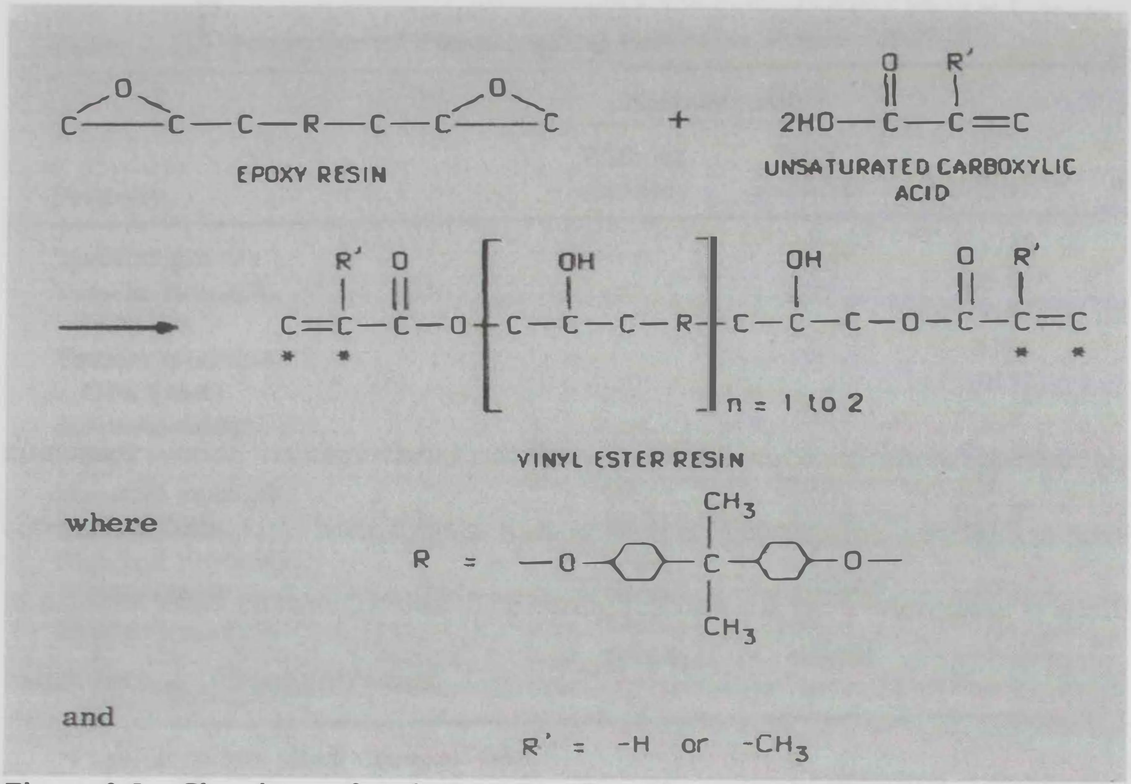

Figure 3.5: Chemistry of a vinyl ester resin. The asterisk (*) denotes unsaturation points (reactive sites) [15]

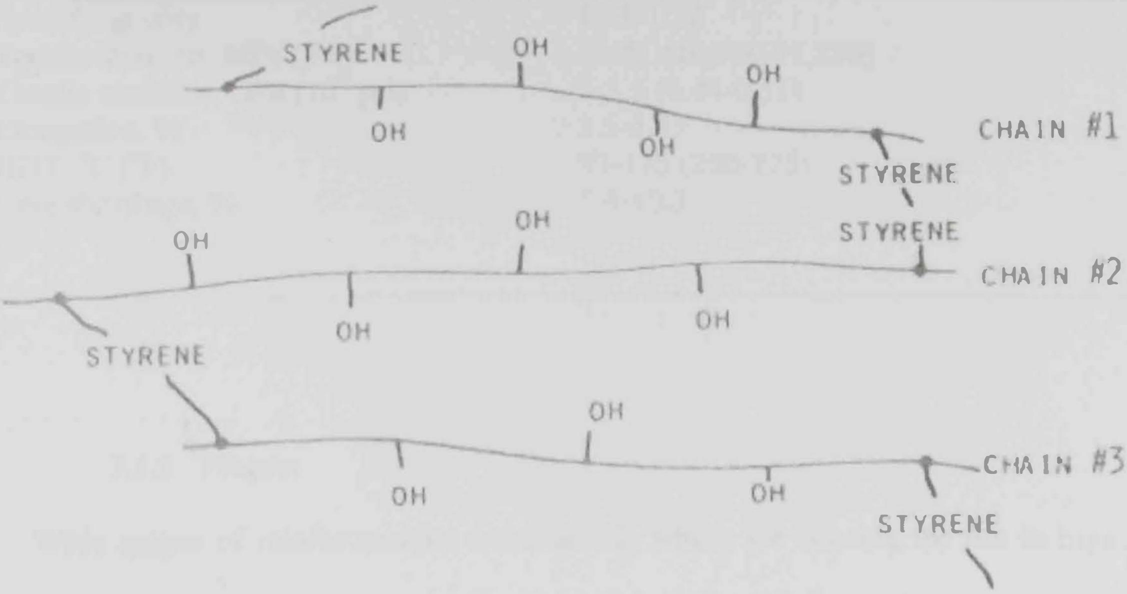

Figure 3.6: Schematic representation of a cross-linked vinyl ester resin [15]

Vinyl ester resins, like unsaturated polyester resins, are dissolved in styrene monomer, which reduces their viscosity. During polymerization, styrene also coreacts with the vinyl ester resin to form cross-links between the unsaturation points in adjacent vinyl ester molecules. The curing reaction for vinyl ester resins is similar to that for unsaturated polyesters.

Vinyl ester resins possess good characteristics of epoxy resins, such as excellent chemical resistance and tensile strength, and of unsaturated polyester resins, such as low viscosity and fast curing. However, the volumetric shrinkage of vinyl ester resins is in the range of 5-10 %, which is higher than that of the parent epoxy resins (Table 3.4). They also exhibit only moderate adhesive strengths compared with epoxy resins. The tensile and flexural properties of cured vinyl ester resins do not vary appreciably with the molecular weight and type of epoxy resin or other coreactants. However, the heat deflection temperature and thermal stability can be improved by using heat-resistant epoxy resins, such as phenolic-novolac types.

Table 3.4: Typical properties of cast vinyl ester resins (at 23°C)

Specific gravity	1.21-1.32
Tensile strength, MPa (Psi)	73-81 (10,500-11,750)
Tensile modulus, GPa (10^6 psi)	3-3.5 (0.44-0.51)
Elongation, %	3.5-5.5
HDT, °C (°F)	93-135 (200-275)
Cure shrinkage, %	5.4-10.3

3.1.2 Fibers:

Wide ranges of reinforcements are available which are suitable for use in liquid composite molding processes. These materials can be obtained in a number of forms, ranging from individual filaments to intermediate products including mats and fabrics. The selection of the appropriate reinforcement material and preform-manufacturing route is based on a balanced consideration of several criteria. The main factors that should be considered are the required level of mechanical properties and the processing characteristics (in particular the reinforcement permeability and suitability for rapid fiber wet-out). Although these factors should be considered when choosing an appropriate reinforcement base material, it should be noted that these properties might also be affected by the preform manufacturing process [16].

3.1.2.1 Types of Fibers:

The type of fibers used depends upon a number of factors related to the intended application. Glass fibers and in particular E-glass, are by far the most common due to their relatively low cost, making them the chosen reinforcement for the majority of automotive applications. Higher performance applications including components for the aerospace industry often utilize carbon fibers, where the increased cost is justified by the associated improvement in mechanical properties. Several man-made (polymer) fibers are also available, the most notable being aramid (often referred to under the DuPont trade-name of Kevlar). Typical properties available with the main forms of reinforcing fibers are included in Table 3.5, whilst the specific mechanical properties (tensile strength or modulus divided by density) are shown in Figure.3.7.

Table 3.5: Properties of commercially available fibers (at room temperature) [15].

	Density, kg/m^3	Tensile modulus, GPa	Tensile strength, GPa	Elongation to break, %	Coefficient of thermal expansion, $K^{-1} \times 10^{-6}$
Glass					
E-glass	2600	72	2.6	3-4	4.8
R-glass	2530	85	3.4		
PAN based Carbon					
HS	1800	235	3.5	1.48	-0.40
HM	1860	370	2.7	0.75	-0.50
IM	1760	300	3.4	1.10	-0.45
Aramid					
Kevlar 29	1440	83	3.6	4.0	
Kevlar 49	1440	124	3.6	2.9	-5.2

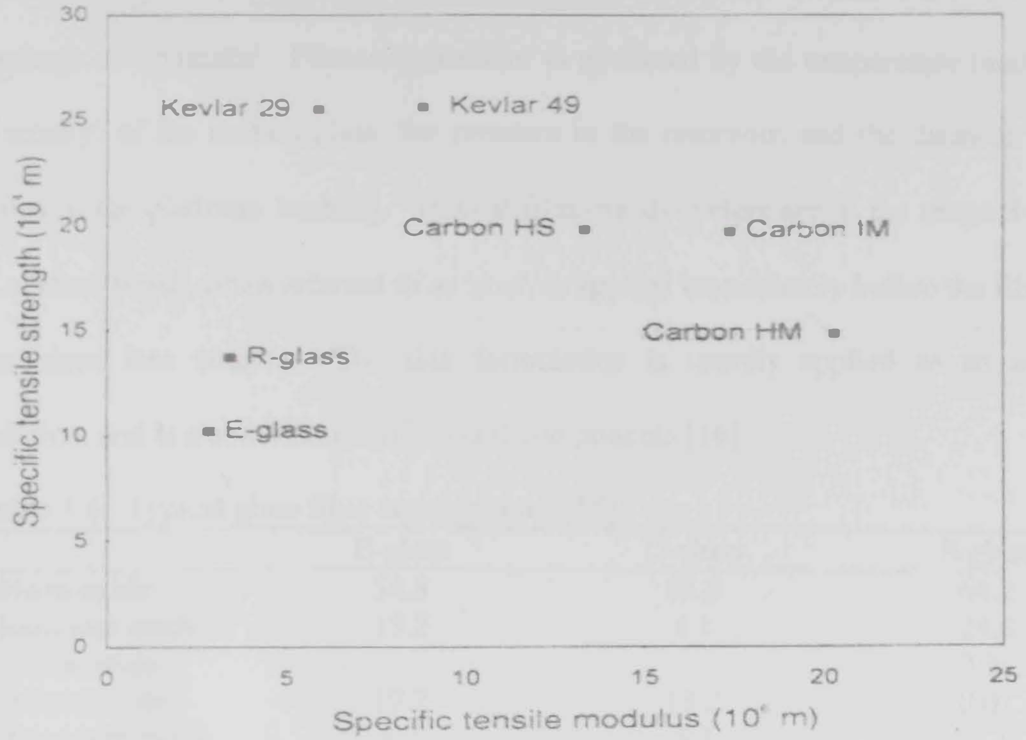

Figure 3.7: Specific longitudinal mechanical properties of reinforcing fibers [16]

3.1.2.1.1 Glass fibers:

Glass fibers are available in a number of forms, each of which is a compound of silica (SiO_2) with a variety of metallic oxides. E-glass fibers, originally developed for their good electrical insulation properties, are by far the most common, providing adequate mechanical properties at relatively low cost. Other (more expensive) forms of glass fiber include C-glass, which has a high resistance to chemical corrosion but a lower strength than E-glass, and S-glass that has a higher mechanical performance. Typical glass fiber compositions are included in Table 3.6.

During the production of glass fibers (shown schematically in Figure. 3.8), continuous filaments are drawn from a reservoir containing the molten raw materials at a temperature usually in excess of 1500°C. The molten glass is fed under gravity into platinum bushings containing several hundred holes. The individual filaments are then cooled with water and combined into strands and wounds on to a forming package or 'spincake'. Filament diameter is governed by the temperature (and hence viscosity) of the molten glass, the pressure in the reservoir, and the diameter of the holes in the platinum bushing. Typical filament diameters are in the range 5-24μm. A surface finish, often referred to as 'size', is applied immediately before the fibers are combined into strands. The size formulation is usually applied as an aqueous solution, and is a combination of several components [16].

Table 3.6: Typical glass fiber compositions [15].

	E-glass	C-class	S-glass
Silicon oxide	54.3	64.6	64.2
Aluminum oxide	15.2	4.1	24.8
Ferrous oxide	_	_	0.21
Calcium oxide	17.2	13.2	0.01
Magnesium oxide	4.7	3.3	10.27
Sodium oxide	0.6	7.7	0.27
Potassium oxide	_	1.7	_
Boron oxide	8.0	4.7	0.01
Barium oxide	_	0.9	0.2

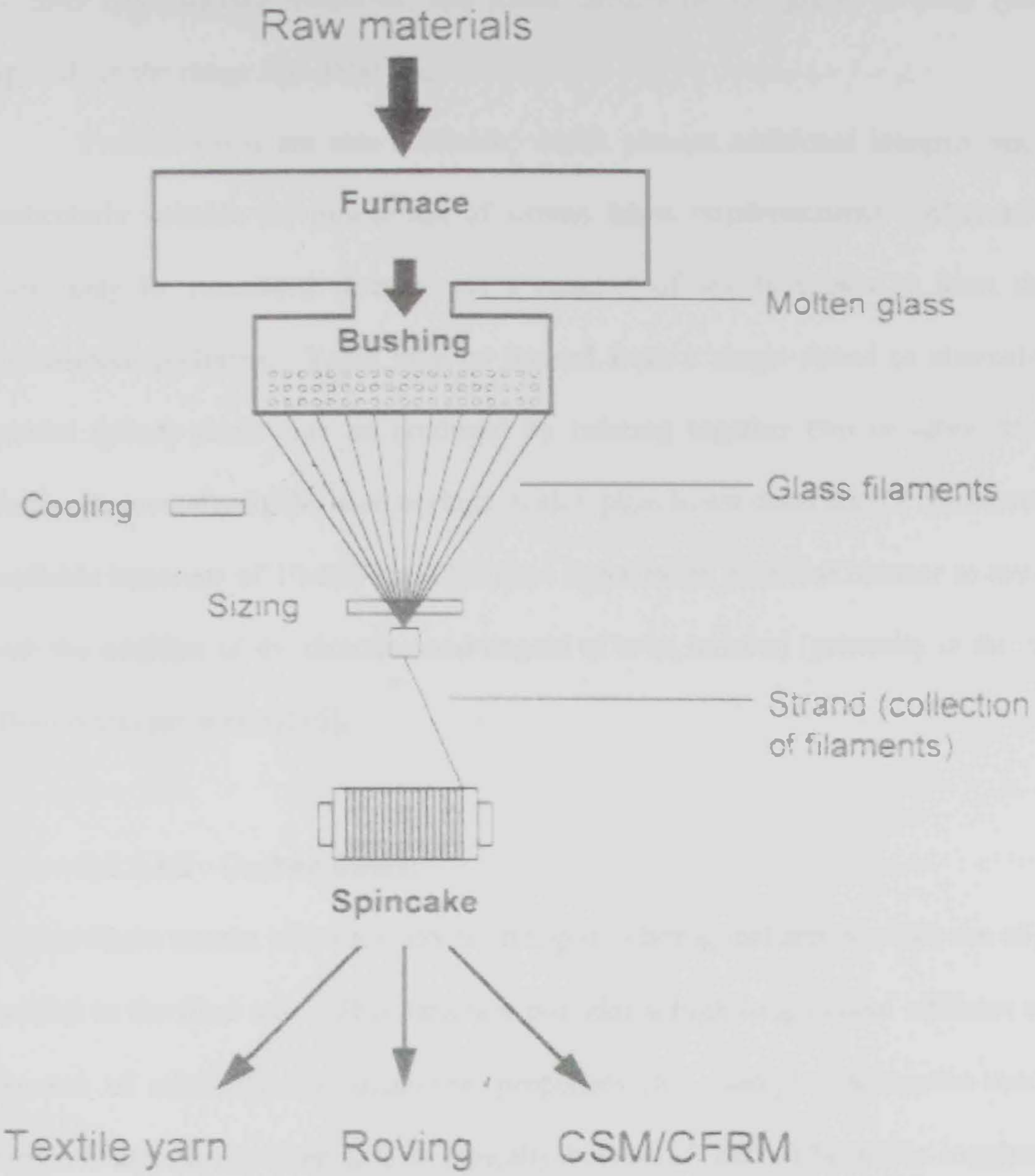

Figure 3.8: Schematic representation of the manufacture of glass fibers [16]

Glass fibers can either be supplied directly as continuous filaments, or alternatively they may be processed to produce a number of reinforcement mats (using either chopped or continuous strands) or fabrics. Continuous fibers are usually supplied as roving on a cylindrical package or cheese (doff). Rovings may be formed by a number of combinations of strands in a separate manufacturing process (assembled rovings) or from a single strand (direct draw rovings). They are specified by fiber type, surface treatment, and linear density in tex (g/km) or yield (yd/lb), typically in the range 300-4800 tex.

Twisted yarns are also available, which possess additional integrity and are particularly suitable for production of woven fabric reinforcements. Alternatively yarns may be processed directly via a number of textile routes to form three-dimensional preforms. Yarns may be formed from a single strand or alternatively heavier (plied) yarns may be produced by twisting together two or more strands. Yarns are generally lighter than rovings, with typical linear densities for commercially available materials of 10-600 tex. They are specified in a similar manner to rovings, with the addition of the direction and degree of twist induced (generally in the range 20-40 twists per meter) [16].

3.1.2.1.2 Carbon fibers:

Carbon fibers consist of carbon atoms arranged in hexagonal arrays which are aligned parallel to the fiber axis. This structure provides a high longitudinal stiffness at the expense of relatively low transverse properties (for example the tensile modulus perpendicular to the fiber axis is typically between 3 and 10% of the longitudinal value). Carbon fibers are produced by thermal degradation of an organic precursor such as rayon, pitch or more usually polyacrylonitrile (PAN). This involves a series of heating operations that are traditionally referred to as stabilization, carbonization, and finally graphitization [16].

During stabilization the precursor is heated to a temperature of up to 400^{o}C in an oxidizing atmosphere (usually air), and is held under tension to promote alignment of the molecular chains. Carbonization involves heating to a temperature of up to 1200^{o}C in an inert atmosphere to convert the precursor into carbon fiber. Finally the fiber is graphitized by heating to temperature of anywhere between 1000 and 3000°C in the absence of oxygen, which increases the tensile modulus by improving the crystalline structure of the fiber. For a particular precursor this temperature, together with the degree of molecular alignment and the degree of conversion from polymer to carbon, determines the mechanical properties of the resulting fiber. A high graphitization temperature (above 2500°C) will result in high stiffness but relatively low strength fiber, traditionally designed as Type I or HM (High Modulus). Lower temperatures (1300-1800°C) are used to produce fibers with a higher strength but lower stiffness, known as HS or Type II. Even lower graphitization temperatures (around 1100°C) are used to produce IM or Type III fibers, which have an intermediate modulus but are significantly cheaper than HM fibers. Although these three categories of fibers form the basis of commercially available materials, nowadays manufacturers offer a far wider range of reinforcements combining low or high strength, strain to failure and stiffness. In particular two additional categories are generally available, namely ultra-high modulus and high strain [16].

Filament diameters are typically in the range 4-10μm. Fibers are usually supplied as continuous tows of between 1K and 12K individual filaments, or alternatively as twisted yarns suitable for textile processing. A surface finishing operation is applied to promote adhesion with the resin and to protect and lubricate the fibers. Once again the surface treatment can be varied depending on the subsequent processing route.

3.1.2.1.3 Aramid fibers:

Ranges of synthetic organic fibers have been developed based on aligned polymer chains that can offer exceptional longitudinal mechanical properties. The most popular material in this category is known as aramid (aromatic polyamid). As mentioned previously aramid fibers have been produced commercially by Du- pont since the early 1970s under the trade name of 'Kevlar', although more recently other manufacturers have introduced similar materials. This reinforcement is particularly suitable where high strength and low weight are required, offering the highest level of specific strength of the common reinforcement fibers (see Figure 2.7). Kevlar fibers are also used for components that require a degree of impact resistance. The basic chemical, poly paraphenylene terephthalamide (PPD-T) is produced from a condensation reaction of paraphenylene diamine and terephthaloyl chloride and belongs to a class of materials known as liquid crystalline polymers. To produce continuous filaments, a solution of PPD-T is extruded through a spinneret and drawn through an air gap, resulting in orientation of the liquid crystalline domain in the direction of flow. This produces a highly aligned structure consisting of long, straight, polymer chains that are oriented parallel to the fiber axis [16].

Due to the presence of strong covalent bonds in the fiber direction and relatively weak hydrogen bonds in the transverse direction, the mechanical properties of aramid fibers are highly anisotropic with longitudinal tensile properties that are significantly higher than transverse properties. The compressive properties are relatively poor, with the compressive strength typically only 20% of the tensile strength. However aramid fibers possess excellent damage tolerance and ballistic behavior and extremely good thermal and dimensional stability. The tensile modulus is a function of the degree of molecular orientation, which may be enhanced by heat treatment under tension to produce materials with a range of properties. Of the Dupont products, Kevlar 49 is most widely used and is said to be suitable for reinforcement with a wide range of resin systems. Kevlar 29 may be used in applications that require particularly good damage tolerance or ballistic stopping performance. Fibers are available as either yarns, typically consisting of 25-1000 filaments, or as rovings (assembled yarns) [16].

3.2 Materials for hip joint implants:

3.2.1 Introduction:

There are different ranges of materials used in the design of the hip joint. Theses materials must have special properties in order to meet the design specifications. These properties depend on the physical and chemical properties of the material.

Many factors must be considered when choosing a biomaterial. Implants which are subject to repeated loading must be manufactured from materials that have adequate mechanical strength in terms of static and fatigue loads. In order to establish this we must have an understanding of the loads, cycles rates and number of loading cycles to be encountered. For a hip joint it can be very difficult to estimate the number of cycles but the loads are easier to estimate [20].

In some cases, properties may be chosen which, on first consideration, may seem less than ideal. It seems logical to produce a hip joint prosthesis that is capable of withstanding the highest possible loads without fracturing. In practice, this may pose a problem for the clinician as, if the joint is subject to an unusually high load, as might be the case during a fall for example, the bone may fracture around the implant and complex surgery may be required to repair the damage. In this context there is an added complication as many hip joint prostheses are used to repair hips in elderly ladies who have poor bone due to osteoporosis. In this case the bone may be too weak to support the prosthesis. Other physical properties to consider include stiffness, hardness, corrosion resistance and wear resistance [20].

3.2.2 Design approach:

Initially implants for hip joints were made using metal alloys such as titanium alloys. However these materials have a high modulus when compared to the bone modulus. Thus problems of bone resorption may occur. With the rapid growth of composite materials, attempts were made to design implants for hip joints using carbon materials, since it is possible to tailor the properties of the composite to match those of the bone. Early work on this subject date back to the early eighties and either long or short carbon fibers have been used coupled with thermoplastic resins such as PEEK or thermoset resins such epoxies. However studies have shown that delaminations problems may occur and faitgue properties of the resulting material are low compared to the metal counterpart.

The innovative aspects of this work consist of using braided fabrics to overcome the problem of plies delamination. Furthermore, hybrid materials are considered to enhance the fatigue properties of the resulting implant and eventually lower the its cost. This combination of different materials are carbon / aramid fibers and glass / aramid fibers.

3.2.3 Characteristics of a fiber-reinforced lamina:

A lamina is constructed by stacking a number of laminas in the thickness (z) direction. We will be using two types of laminates:

1) Unidirectional laminates: In unidirectional laminates, fiber orientation angle is the same in all laminas (Figure 3.9). In unidirectional 0^o laminates for example, $\theta = 0^o$ in all laminas.

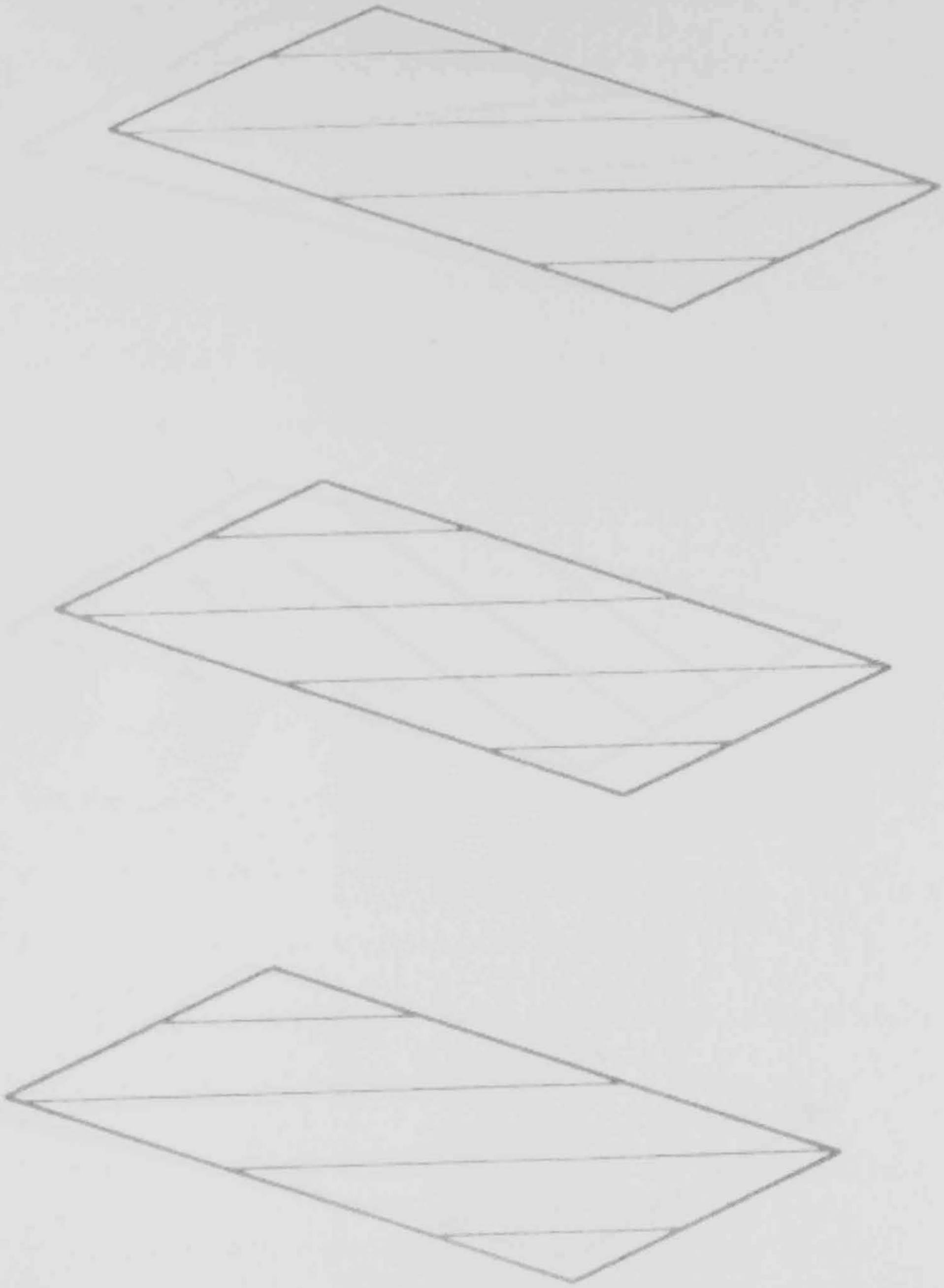

Figure 3.9: Unidirectional laminate [16]

2) Angle-ply laminates: In angle-ply laminates, fiber orientation angles in alternate layers are …../ θ /- θ / θ / - θ / ….. when $\theta \neq 0$ or 90^{o} (Figure 3.10).

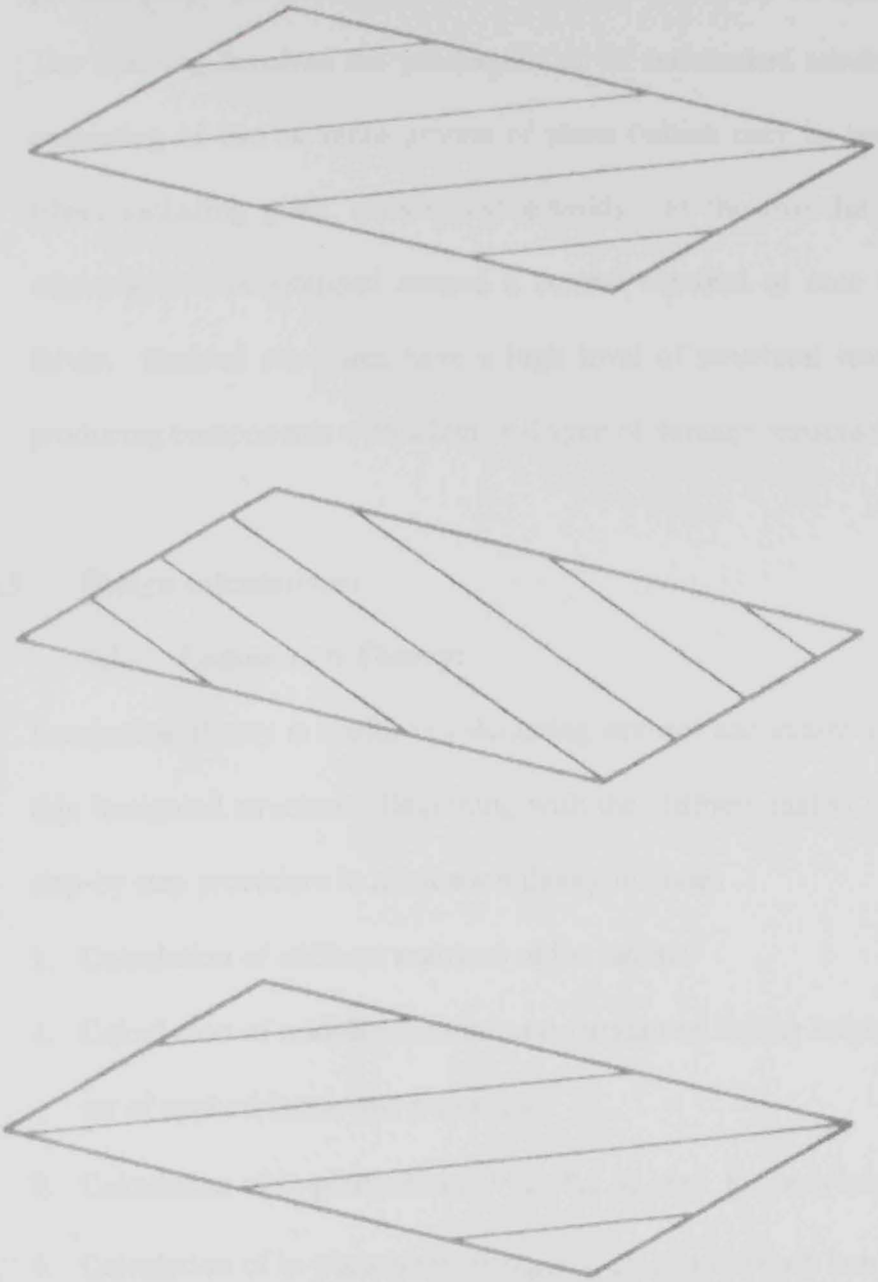

Figure 3.10: Angle-ply laminate [16]

The major problem with the unidirectional laminates is the delaminatinon (i.e., separation between various laminas). Delamination occurs as a result of high interlaminar stresses. As a result of delamination, local stresses in the 0° layers increase, since the delaminated off-axis plies cease to share 0° load. Additional stresses in 0° layers, in turn, cause fiber failure and accelerate the fatigue failure process [15]. To overcome the delamination problem, we use braided structure. The braiding involves the production of an interlocked reinforcement structure consisting of two or more groups of yarns (which may be based on a range of fibers including glass, carbon and aramid). In the two dimensional braiding, where yarns are wrapped around a central mandrel or core to form a tubular fabric. Braided structures have a high level of structural integrity, resulting in producing components with a higher degree of damage resistance [17].

3.3 Design calculations:

3.3.1 Lamination Theory:

Lamination theory is useful in calculating stresses and strains in each lamina of a thin laminated structure. Beginning with the stiffness matrix of each lamina, the step-by step procedure in lamination theory includes

1. Calculation of stiffness matrices of the lamina
2. Calculation of midplane strains and curvatures for the laminate due to a given set of applied forces and moments
3. Calculation of in-plane strains ™$_{xx}$, ™$_{yy}$,γ_{xy} and for each lamina
4. Calculation of in-plane stresses σ_{xx}, σ_{yy} , τ_{xy} and in each lamina

Assumptions:

Basic assumptions in the lamination theory are

1. The laminate is thin and wide (width > thickness)
2. A perfect interlaminar bond exists between various laminas
3. The strain distribution in the thickness direction is linear
4. All laminas are macroscopically homogeneous and behave in a linearly elastic manner

3.3.2 Elastic properties of a lamina

A. Unidirectional continuous fiber 0^o lamina

Elastic properties of a unidirectional continuous fiber 0^o lamina (Figure 3.11) are calculated from the following equations [14]:

Longitudial modulus (E_{11}):

$$E_{11} = E_f * V_f + E_m * V_m \qquad (2.1)$$

Where

E_{11}= longitudinal modulus

E_f= fiber tensile modulus

V_f= fiber volume fraction

E_m = matrix tensile modulus

V_m = matrix volume fraction

$V_m = 1 - V_f$

Major poisson's ratio (ν_{12}):

$$\nu_{12} = \nu_f * V_f + \nu_m * V_m \qquad (2.2)$$

Where

ν_{12}= major Poisson's ratio

ν_f = fiber poisson's ratio

ν_m = matrix poisson's ratio

Transverse modulus (E_{22}):

$$E_{22} = \frac{E_f * E_m}{E_f * V_m + E_m * V_f} \qquad (2.3)$$

Where

E_{22} = transverse modulus

Minor Poisson's ratio (ν_{21}):

$$\nu_{21} = \frac{E_{22}}{E_{11}} \nu_{12} \tag{2.4}$$

Where

ν_{21} = Minor poisson's ratio

Shear modulus (G_{12}):

$$G_{12} = \frac{G_f * G_m}{G_f * v_m + G_m * v_f} \tag{2.5}$$

Where

$$G_f = \frac{E_f}{2(1+\nu_f)}$$

$$G_m = \frac{E_m}{2(1+\nu_m)}$$

Where

G_{12} = shear modulus

G_f = fiber shear modulus

G_m = matrix shear modulus

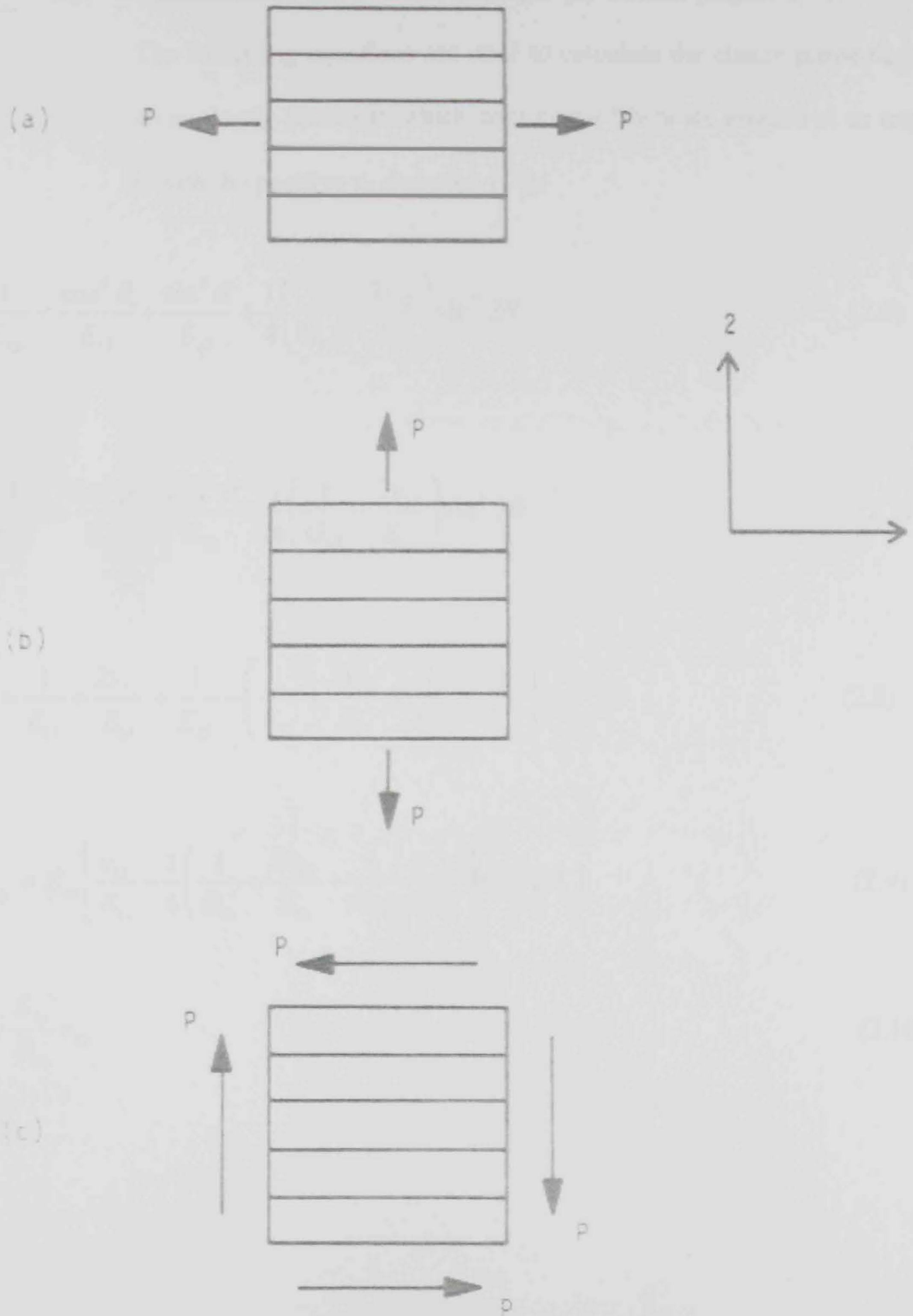

Figure 3.11: Application of (a) longitudinal force, (b) transverse force, and (c) shear force on a unidirectional continuous fiber 0^{o} lamina [15].

B. Unidirectional continuous fiber angle-ply lamina (Figure 3.12):

The following equations are used to calculate the elastic properties of an angle-ply lamina in which continuous fibers are aligned at an angle θ with the positive x- direction [14]:

$$\frac{1}{\mathrm{E_{xx}}}=\frac{\cos^4\theta}{E_{11}}+\frac{\sin^4\theta}{E_{22}}+\frac{1}{4}\left(\frac{1}{G_{12}}-\frac{2\nu_{12}}{E_{11}}\right)\sin^2 2\theta \tag{2.6}$$

$$\frac{1}{\mathrm{E_{yy}}}=\frac{\sin^4\theta}{E_{11}}+\frac{\cos^4\theta}{E_{22}}+\frac{1}{4}\left(\frac{1}{G_{12}}-\frac{2\nu_{12}}{E_{11}}\right)\sin^2 2\theta \tag{2.7}$$

$$\frac{1}{\mathrm{G_{xy}}}=\frac{1}{E_{11}}+\frac{2\nu_{12}}{E_{11}}+\frac{1}{E_{22}}-\left(\frac{1}{E_{11}}+\frac{2\nu_{12}}{E_{11}}+\frac{1}{E_{22}}-\frac{1}{G_{12}}\right)\cos^2 2\theta \tag{2.8}$$

$$\nu_{xy}=E_{xx}\left[\frac{\nu_{12}}{E_{11}}-\frac{1}{4}\left(\frac{1}{E_{11}}+\frac{2\nu_{12}}{E_{11}}+\frac{1}{E_{22}}-\frac{1}{G_{12}}\right)\sin^2 2\theta\ \right] \tag{2.9}$$

$$\nu_{yx}=\frac{E_{yy}}{E_{xx}}\nu_{xy} \tag{2.10}$$

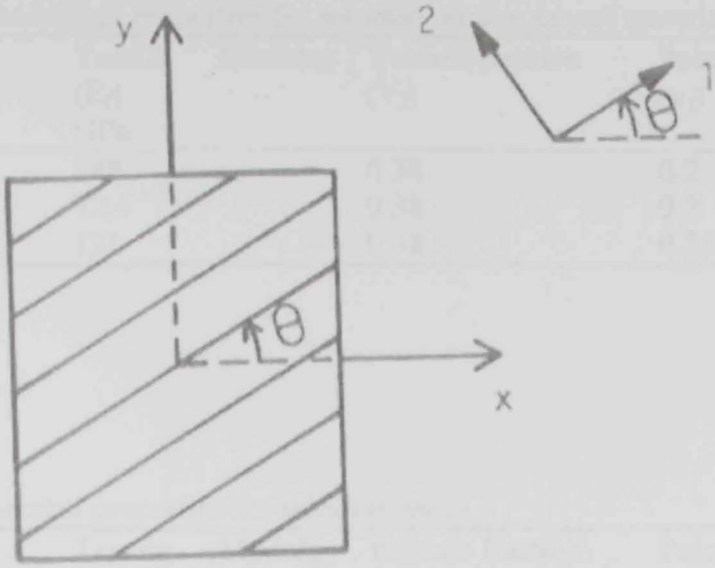

Figure 3.12: Angled unidirectional continuous fiber lamina [15].

3.4 Theoretical Calculations:

Tables 3.7 and 3.8 show the mechanical properties for selected reinforcement materials and selected resins, respectively. These mechanical properties are used to calculate the elastic properties of both unidirectional continuous fiber 0^o lamina and unidirectional continuous fiber angle-ply lamina.

Table 3.7: Mechanical properties for selected reinforcement materials

Fiber	Tensile Modulus (E_f) GPa	Volume fraction (V_f)	Poission's ratio (ν_f)
AS-4 carbon	248	0.38	0.2
E-glass	72.4	0.38	0.2
Aramid kevlar 49	131	0.38	0.35

Table 3.8: Mechanical properties for selected resins

Resin	Tensile Modulus (E_m) GPa	Volume fraction (V_f)	Poission's ratio (ν_f)
Epoxy	3	0.62	0.3
Vinyl ester	3.25	0.62	0.3
PEEK	3.24	0.62	0.4

1. Elastic properties of a unidirectional continuous fiber 0° lamina:

A detailed example of calculating the elastic properties of a unidirectional continuous fiber 0° lamina is given below.

Mechanical properties of the carbon fibers and epoxy:

E_f (fiber tensile modulus) = 248 GPa

V_f (fiber volume fraction) = 0.38

E_m (matrix tensile modulus = 3 GPa

V_m (matrix volume fraction) = 1-Vf = 0.62

ν_f (fiber poisson's ratio) = 0.2

ν_m (matrix poisson's ratio) = 0.3

Calculate E_{11}, E_{22}, ν_{12}, ν_{21},and G_{12} using equations 2.1 through 2.5

E_{11}= (248) * (0.38) + (3) * (1-0.38) = **96.1 GPa**

E_{22}= (248) * (3) / [(248) * (0.62) + (3) * (0.38)] = **4.80 GPa**

ν_{12}= (0.2) * (0.38) + (0.3) * (0.62) = **0.262**

ν_{21}= (4.80 / 96.1) * (0.262) = **0.013**

In order to calculate G_{12} , we need to know the values of G_f and G_m

G_f = 248 / [2* (1+0.2)] = 103.3 GPa

G_m = 3 / [2* (1+0.3)] = 1.15 GPa

G_{12}= (103.3) * (1.15) / [(103.1) * (0.62) + (1.15) * (0.38)] = 1.84 GPa

For complete calculations of the elastic properties of a unidirectional continuous fiber, please refer to appendix A.

2. Elastic properties of a unidirectional continuous fiber (hybrid fabrics) angle-ply lamina:

A detailed example of calculating the elastic properties of a unidirectional continuous fiber angle-ply lamina is given below.

$\theta = 15^o$

E_{11} = 96.1 GPa

E_{22} = 4.80 GPa

G_{12} = 1.84 GPa

ν_{12} = 0.262

Cos $\theta = 15^o$ = 0.8705

Sin $\theta = 15^o$ = 0.00448

$Sin^2 2\theta$ = 0.25

$Cos^2 2\theta$ = 0.749

Calculate E_{xx}, E_{yy}, ν_{xy}, ν_{yx}, and G_{xy} using equations 2.6 through 2.10

$1/ E_{xx}$ = 0.8705/96.1 + 0.00448/4.8 + 1/4*(1/1.84-0.524) *0.25 = 0.43618

E_{xx} = 22.9 GPa

$1/ E_{yy} = 0.00447/96.1 + 0.8705/4.8 + 1/4*(1/1.84-0.524) *0.25 = 0.215027$

$E_{yy} = 4.65$ GPa

$1/ G_{xy} = 1/96.1 + 0.524/96.1 + 1/4.8 - (1/96.1 + 0.524/96.1 + 1/4.8 - 1/1.84) *$

$(0.749) = 0.463337$

$G_{xy} = 2.15$ GPa

$\nu_{xy} = 22.9 * [0.262/96.1 - 1/4 * (1/96.1 + 0.524/96.1 + 1/4.8 - 1/1.84) *(0.25)]$

$=$ **0.473128**

$\nu_{yx} = (4.65/22.9)* (0.473128) =$ **0.095974**

For complete calculations of the elastic properties of a unidirectional continuous fiber (hybrid fabrics) angle-ply lamina, please refer to appendix A.

Chapter Four

Samples Manufacturing and Testing

4.1 Introduction:

The selection of a manufacturing process is the first successful step in designing a composite material. This is important because it affects many factors such as cost, production volume, production rate, and adequacy of manufacturing process to produce the desired structure [17]. In general, the manufacturing process depends on the type of the resin and fibers, the required temperature to make the part and to cure the resin, and the economic cost of the process.

Due to inadequacy of manufacturing process, we have limited our manufacturing process of composite samples to two manufacturing techniques. The two techniques will be presented later in this chapter.

4.2 Materials used in Sample Preparation:

4.2.1 Reinforcement (Fibers):

Two types of reinforcements were used in this experiment. The first type was a woven roving E-glass fibers, which is a coarse drapable fabric in which continuous roving are woven in two mutually perpendicular directions. The stack consists of 5 plies having a surface weight density of 600 g/m^2 supplied by CS-INTERGLASS L.L.C., Dubai, U.A.E. The second type of the reinforcement was a hybrid fabric, which is combination of aramid and carbon fibers. The aramid fibers used in this experiment were made of high modulus fibers. The principal advantage of using hybrid fabrics is that they are highly flexible. The surface weight density for the hybrid is 205 g/m^2 supplied by CS-INTERGLASS L.L.C., Dubai, U.A.E.

4.2.2 Resins:

One type of resin was used in the experiments. The commercial name for this resin is SWANCOR 901 (Bisphenol – A type). SWANCOR 901 is a general-purpose vinyl ester resin, resistant to a broad range of acid, base and salt solutions, commonly up to 100° C. Various viscosity versions of SWANCOR 901 can be used for laminating, resin transfer molding, pultrusion and filament winding. The vinyl ester was promoted with 3 pph of 6% cobalt solution and catalyzed with 1.5 pph of 55% methyl ethyl ketone peroxide (Table 4.1). Mechanical properties of SWANCOR 901 resin are listed in table 4.2.

Table 4.1: SWANCOR 901-Vinyl Ester Resin Specifications

Appearance	Clear
Solid content	55 ± 1 %
Viscosity	350 - 550 cps (LVT -# 3-60 rpm / 25° C)
Specific Gravity	1.04 ± 0.01
Gel time	15 ~ 25 min. (25°C,6%Cobalt:0.4 phr,100%DMA:0.05phr,55%MEKPO:1.2phr)
Shelf Life	6 months (under 25°C)

Table 4.2: Mechanical properties of SWANCOR 901 vinyl ester resin

Properties	**Value**	**Unit**	**Test Method**
Tensile Strength	11000 ~ 14000	Psi	ASTM D-638
Tensile Modulus	4.8 ~ 5.2 x 10^5	Psi	ASTM D-638
Tensile Elongation	5.0 ~ 6.0	%	ASTM D-638
Flexural Strength	17000 ~ 20000	Psi	ASTM D-790
Flexural Modulus	4.5 ~ 5.0 x 10^5	Psi	ASTM D-790
Volume Shrinkage	8.0	%	ASTM D-2566
Heat Distortion Temperature	100 - 102	°C	ASTM D-648
Barcol Hardness	35 ± 3		ASTM D-2583
Impact Strength (Charpy Test)	5 ~ 8	Kg-cm/cm^2	ASTM D-256

4.3 Sample preparation:

We used two processing techniques in order to manufacture the samples. These techniques were hot press molding and vacuum infusion molding. We divided the samples into three groups and each group contains eight samples. While some samples were kept immersed in a physiological solution for a period of eight weeks, others were used as a virgin sample. This physiological solution is also known as Ringer's solution. It is a balanced aqueous solution that contains chloride, sodium, potassium, bicarbonate, and phosphate ions (Table 4.3) that is used in physiological experiments to provide a medium essentially isosmotic to many animal tissues. This is a solution of salts of set composition and concentration (Table 4.3) that mimics the composition of animal body fluids. The reason that we immersed the samples into the physiological solution was to compare the mechanical properties of the implanted composites with the virgin one.

Table 4.3: Ringer's solution specification

Composition	Concentration Molecular	Weight (g)	Volume (Liter)
NaCl	135 mM	58.44	7.55
KCl	5 mM	74.50	0.3725
$MgSo_4$	1 mM	246.48	0.24648
Glucose	11 mM	198.18	2.17998
$Na2HPo_4$	1 mM	141.96	0.14196
$NaHCo_3$	15 mM	84.0	1.266
$CaCl_2$	25 mM	430.38	1.0759

4.4 Processing Techniques:

4.4.1 Hot Press:

In this process dry reinforcement was placed on a clean aluminum table, then the predetermined amount of reactive resin was poured on the top of the reinforcement. We had to make sure that the reinforcement was impregnated by brushing the resin immediately after pouring it on the top of the reinforcement materials (5 layers) in a mold cavity. Then the compression molding operation began after closing the mold (Figure 4.1). Processing temperature was set at 150^{o} C according to the selected cure cycle. In order for the reinforcement to cure, an applied load of 590 kg was set by the hot press machine control. Processing time was set to 15 minutes for the processing temperature and the applied load. Once the time was completed, the mold is opened and the part was removed (Figures 4.2 & 4.3).

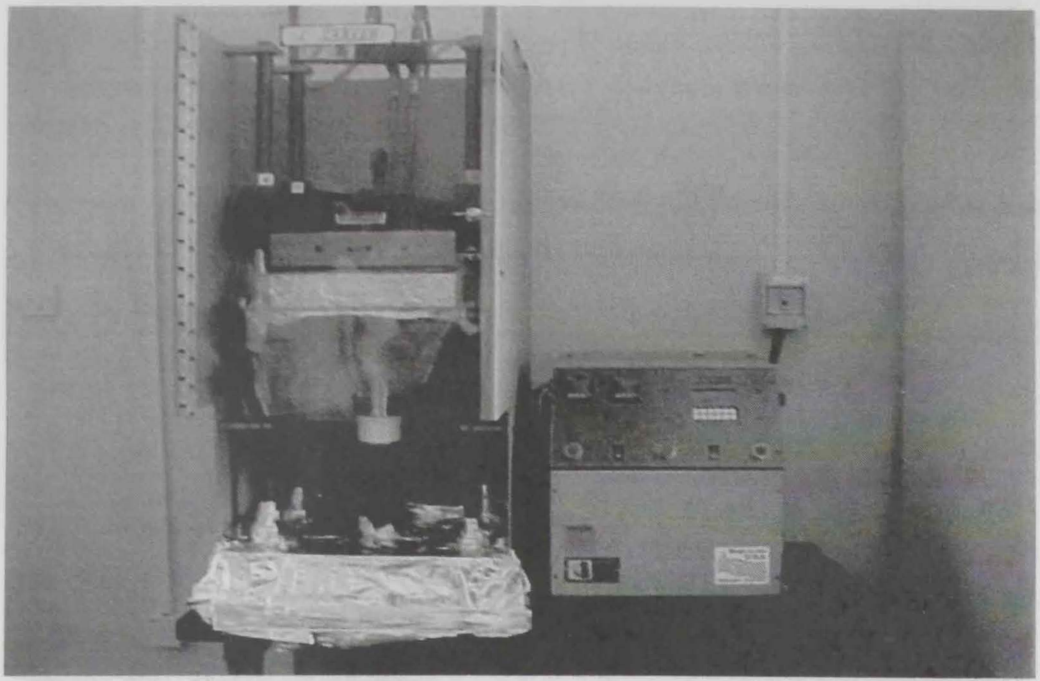

Figure 4.1: Hot press machine

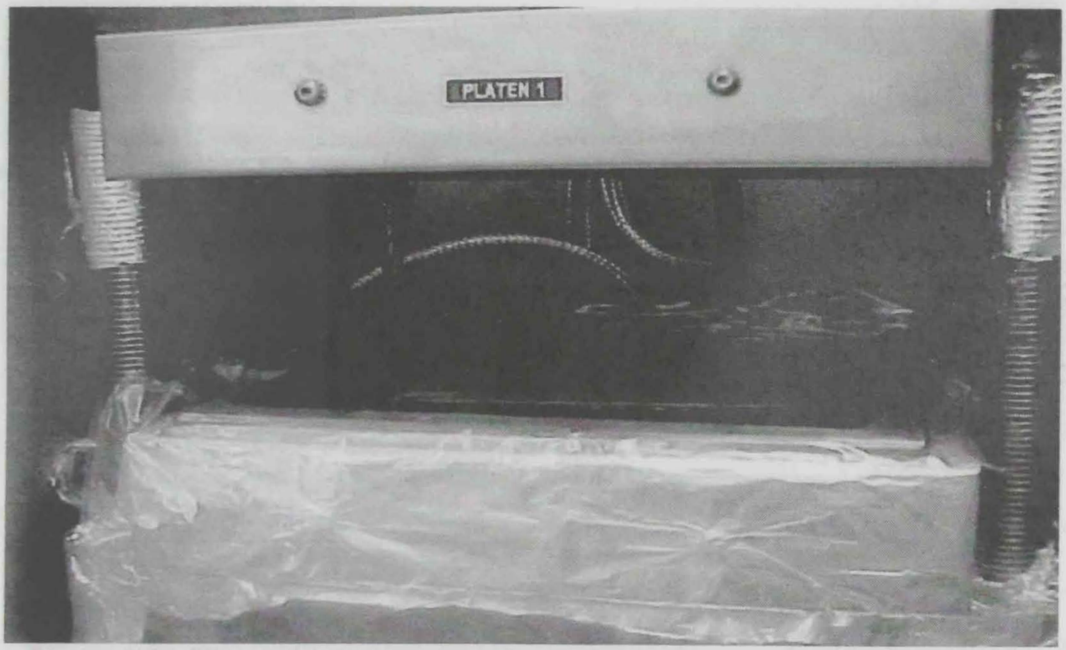

Figure 4.2: The mold cavity opened containing the sample after hot pressing

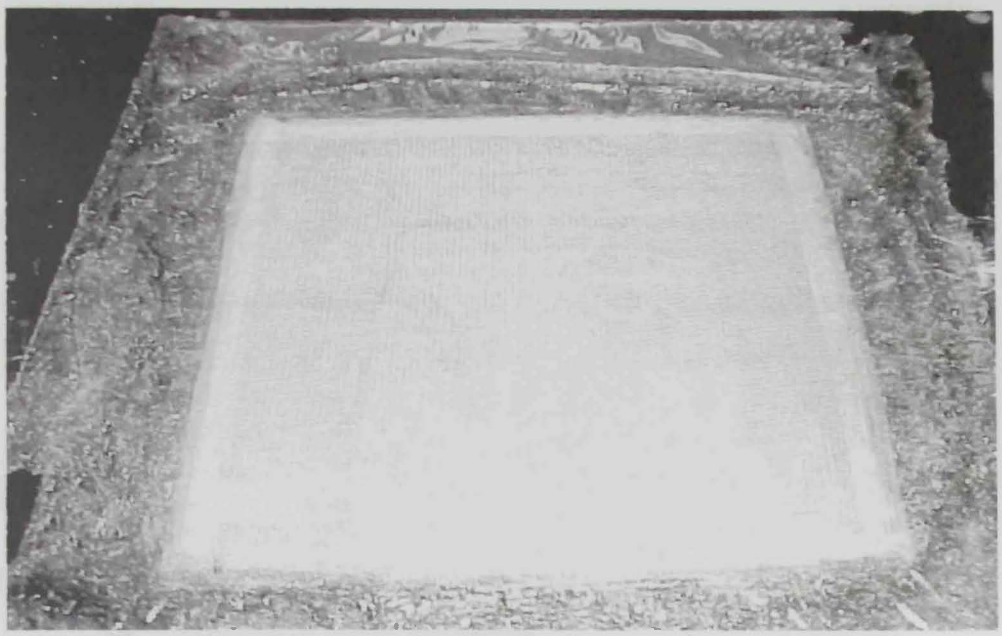

Figure 4.3: Glass sample after the hot pressing

4.4.2 Vacuum Infusion:

In this process, an aluminum table was used as a single sided mold. This aluminum table was designed to be thermally stable. The dry reinforcement was built up and hand placed on this mold and covered. A polymeric bag was sealed using a sealant tape, and two connections were made via a connection fitted to the mold. One connection was a vacuum line (pressure of 1 bar) to remove air and volatiles, while the other connection was used to consolidate individual layers into a laminate (Figures 4.4, 4.5, & 4.6).

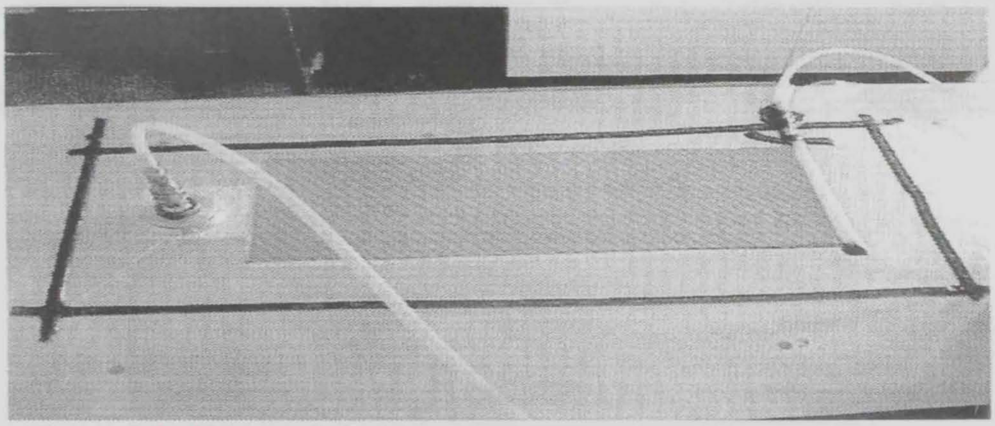

Figure 4.4: Vacuum Infusion set-up

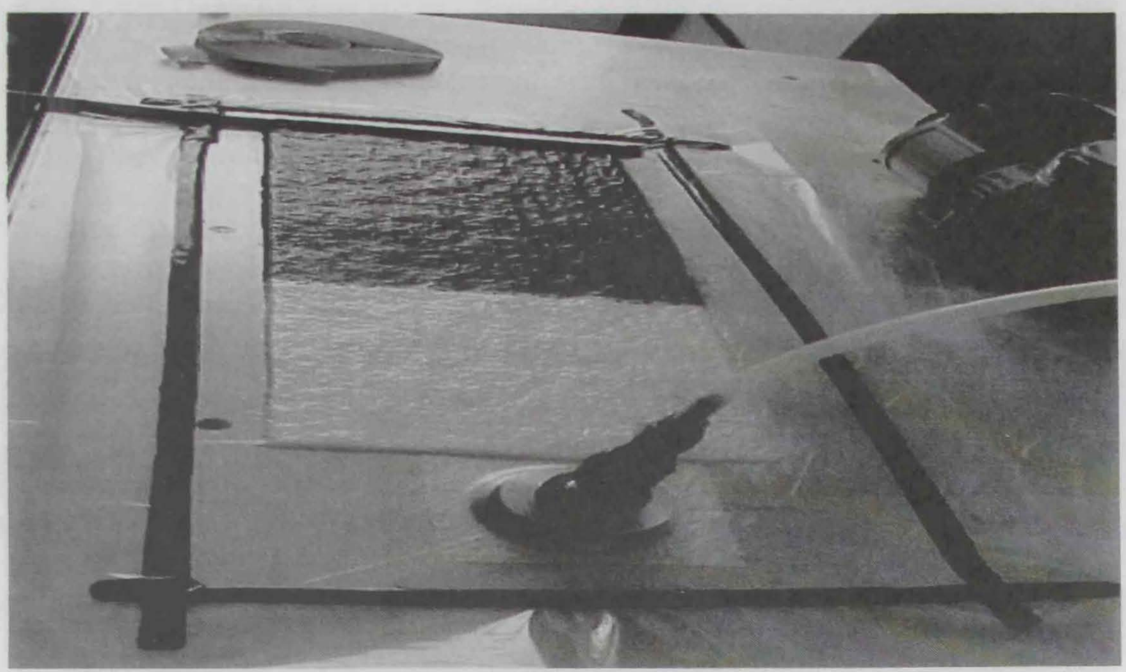

Figure 4.5: Laminate is being infiltrated

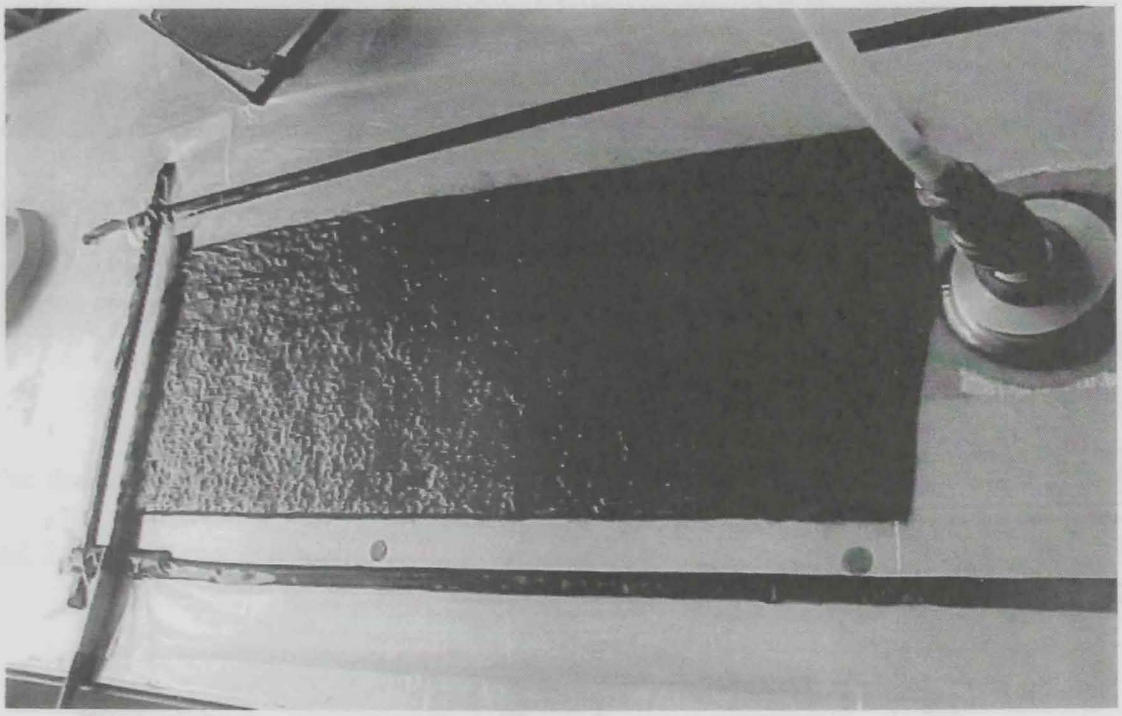

Figure 4.6: Laminate is fully infiltrated

4.5. Fiber Content

The mechanical properties of a fiber-reinforced composite material are controlled by the relative fiber volume fraction contained in the composite material. The method used to determine the fiber volume fraction was the ignition loss method (ASTM- D 2854-68). This method is used for fibers that do not loss weight at high temperatures, such as glass fibers. In this method, a selected test sample was cut with manual hacksaw, and then cured resin was burned off from a small test sample at 565° C in a muffle furnace for three hours. From this test, the fiber weight fraction (w_f) is determined by comparing the weights of the test sample before and after the removal of the resin. Using this value and other related values, we could determine the fiber volume fraction (v_f) by using the following equation:

$$v_f = \frac{w_f / \rho_f}{(w_f / \rho_f) + (1 - w_f) / \rho_f} \qquad 3.1$$

Where

w_f = fiber weight fraction
$(1-w_f)$ = matrix weight fraction
ρ_f = fiber density
ρ_m = matrix density

The density values that were used in this experiment for resin and fiber were 1.1 g/ml and 2.54 g/ml, respectively.

4.6 Testing:

In order to investigate the mechanical properties of different fiber reinforced composite structures, the strength and modulus were determined. Three point bending tests were performed on universal tensile testing MTS machine at the UAE university lab (Figures 4.7 & 4.8) as recommended by ASTM standard (ASTM D 303-00). Test specimens were cut with shearing machine with parallel cutting blades. Appendix D represents sample dimensions for the specimens used in these experiments.

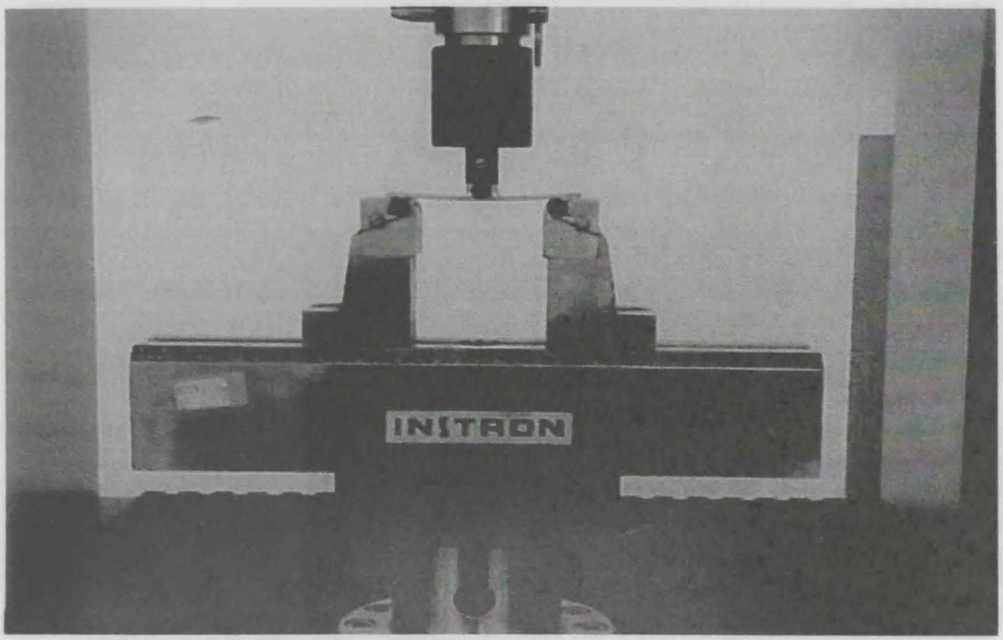

Figure 4.7: Sample under test

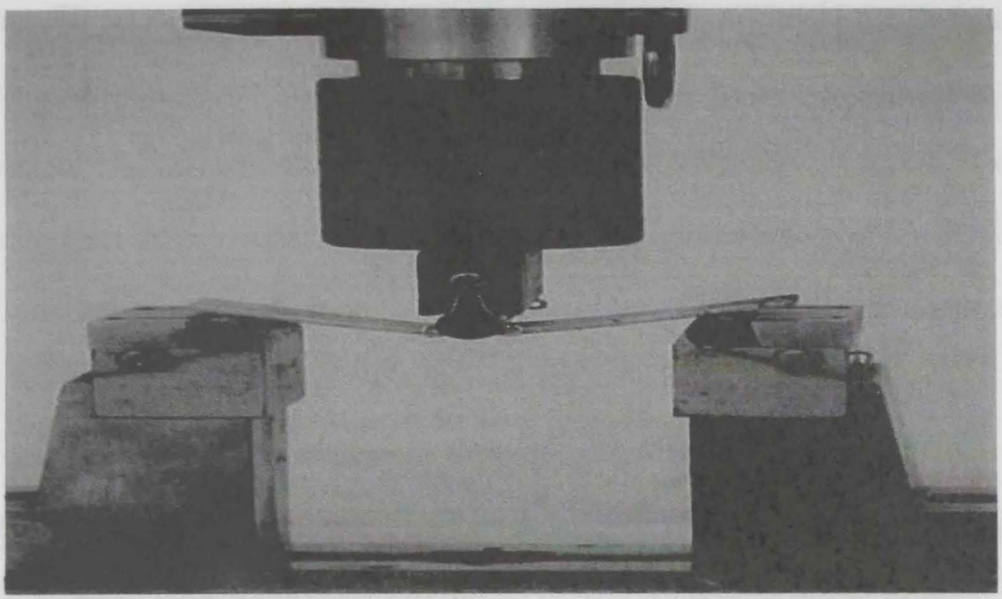

Figure 4.8: Deformed sample

Chapter Five

Results and Discussions

5.1 Introduction:

The performance of an engineering material is judged by its properties and behavior under tensile, compressive, shear, fatigue and other loading conditions. It may also include some adverse environment tests like immersion of the material in the physiological solution. In this chapter, we will describe the performance of the hybrid composite material that we used in this project. The emphasis will be focused on the general trends observed in the properties and behavior. The chapter will address the following topics: mechanical properties of the material that was used, the effects of the adverse environment on the implant, using scanning electron microscope technique and fatigue testing.

5.2 Adverse Environment Tests:

In order for the implanted material to show excellent performance, it has to satisfy certain adverse environment factors. Some of these adverse environment factors include corrosive fluids and moisture. Recent researches identified the surrounding body fluids as a possible corrosive medium [3]. These environmental conditions may cause the mechanical and physical properties of a fiber-reinforced composite material to degrade. The reasons behind this degradation are:

- Volumetric expansion due to moisture absorption can lead to physical and / or chemical degradation of the polymeric matrix, such as reduction in modulus.
- Due to diffusion of water or other fluids into the fiber-matrix interface, debonding will occur at the interface. As a result, this may cause reduction in fiber strength due to stress corrosion.

In this section, we will consider the effect of weight gain for the specimens immersed in the physiological solution and the effect of the immersion time on the composite performance.

5.2.1 Weight Gain:

It is clear from figure 4.1 that weight gain occurred for the glass fiber specimens made by vacuum infusion after the immersion in the physiological solution for a period of eight weeks. We can see from the graph that the weight gain increased rapidly at the beginning of immersion and reached a steady state after 8 weeks. The maximum weight gain for immersed glass specimen made by hot press technique was 1%. For the specimen made by vacuum infusion technique, the maximum weight gain for this immersed specimen was almost 4 %. We note that there is a difference in weight gain between vacuum infusion technique and hot press technique. The reason for this difference is related to the processing techniques that were used to manufacture the specimens. In hot press technique, the preheated mold and the curing cycle selected was probably enough to achieve full cure of the composite specimens. Whereas specimens manufactured by the vacuum infusion technique, full cure will not be achieved immediately, thus causing leaching of the un reacted resin which increase the rate of water diffusion within the matrix. Thus, higher weight gain will be recorded.

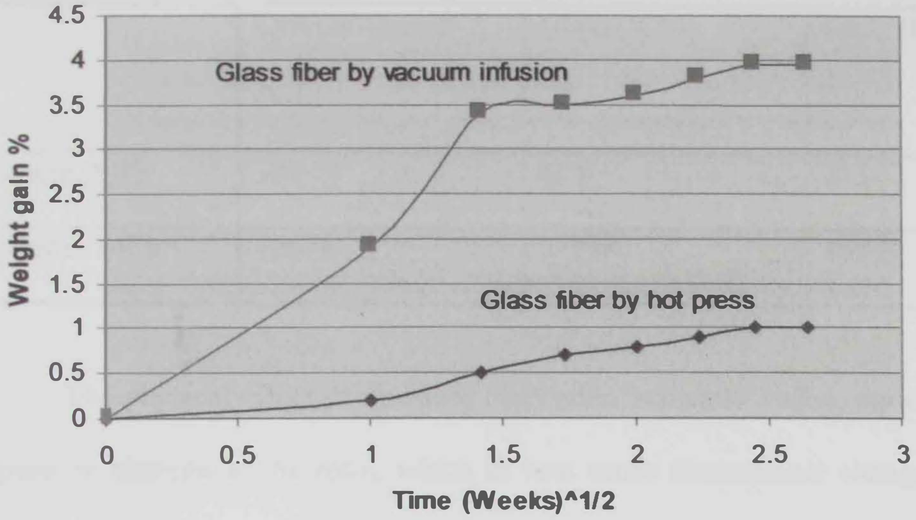

Figure 5.1: Water absorption gain for immersed glass fiber made by vacuum infusion and hot press.

According to Figure 5.1, the weight gain and the moisture diffusion will reach an equilibrium (saturation) level after several days of immersion in the physiological solution.

Table 5.1: Flexural properties for samples immersed in solution

	Carbon/Aramid (V.I.)	Glass (V.I.)	Glass (Hot Press)
Strength, MPa	310 ± 28	445 ± 24	264 ± 41
Modulus, MPa	37791 ± 5814	19347 ± 1775	20308 ± 1081

Table 5.2: Flexural properties for virgin samples

	Carbon/Aramid (V.I.)	Glass (V.I.)	Glass (Hot Press)
Strength, MPa	397	495	215
Modulus, MPa	45674	21288	19999

The physical effect of moisture absorption is clearly visible through the volumetric expansion changes in the resin, which in turn cause dimensional changes in the material. These changes in the material reflected in reduction and degradation of the material properties, such as strength and modulus. This is very obvious through the flexural properties values tabulated in Tables 5.1 and 5.2. We can see that the strength for carbon / aramid dropped by 27.7 %. Also, the modulus reduced by 20.8 %. We can conclude that immersion of the specimens in the physiological solution has a tremendous potential to accelerate the degradation process via water absorption within the matrix. Please refer to appendix C for a complete results for specimens immersed in the physiological solution.

Unfortunately, this was not the case for glass specimen made by hot press technique. We found that the strength of the immersed specimens was greater than the strength of the virgin specimens. In other words, strength reduction did not occur in the immersed specimens as we expected. In order to explain this unexpected result, we have to remember that resin is used in fibers to act as load-transfer mechanism as well as to protect the fibers from being destroyed. So, we believe that the amount of resin that was supposed to impregnate the fiber matrix was inadequate to protect the fibers from being destroyed. As a consequence, the lack of sufficient resin available in the fiber-matrix interface caused deterioration and strength reduction. This is confirmed through volume fraction values calculated for the material. The volume fractions for immersed glass fiber specimen and virgin specimen were 58% and 65.8%, respectively. This result clearly shows that lacks of proper fiber coating may drastically affects the performance of the composite since a good resin to fiber interface is necessary in order for the composite to deliver its expected performance. Actually, when designing composite structure, a major assumption used is the existence of a perfect bond between the matrix and the fiber.

5.3 Scanning-electron microscopy:

Scanning electron microscopy (SEM) was used in this study to achieve two main objectives. First of all, to examine the surface of fractured virgin specimens and specimens immersed in the physiological solution in order to evaluate how longer immersion time and exposure to a relatively corrosive environment may affect the way the material fails. Secondly to understand how the combined action of longer immersion time and a dynamic load may affect the performance of the implant material.

5.3.1 Static loading fracture

Here the observed fracture surfaces resulted from the three point bending tests. Specimens were produced using the hot press molding process and the vacuum infusion molding process. Layers near the top surface will be in compression and layers close to the bottom will be in tension. Observation was made on the cross section and the region surrounding the fractured surface.

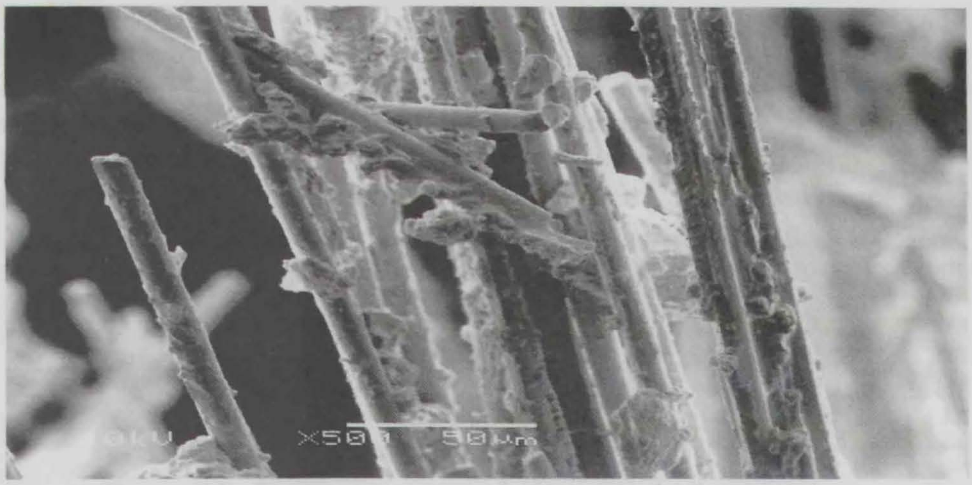

Figure 5.2: Fractured immersed glass sample (hot press)

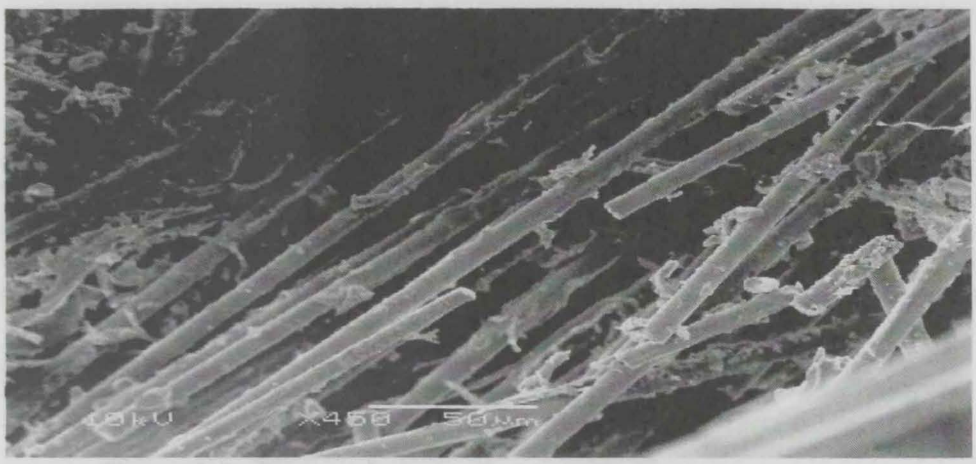

Figure 5.3: Fractured virgin glass sample (hot press)

When comparing the virgin and immersed specimens as shown in Figures 5.2 and 5.3, the following observation can be drawn:

- For both immersed and virgin samples, failure occurs as a result of matrix cracking.
- The surface of fibers for immersed samples was covered with matrix fragments showing that immersion is increasing the ductility of the matrix.

This is also confirmed when comparing the size of the fragmentated resin. The immersed samples have larger fragments than the virgin ones.

Similar observations can be drawn for specimens manufactured by the vacuum infusion molding process. When comparing fractured surfaces as shown in Figures 5.4 and 5.5, it appears that immersion will result in resin softening due to water diffusion in the matrix.

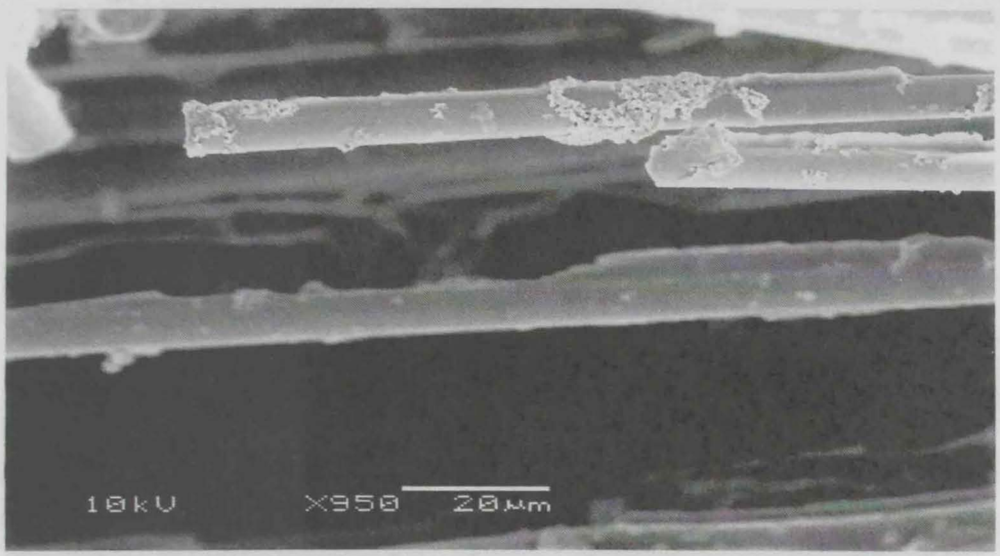

Figure 5.4: Fractured surface for an immersed sample (vacuum infusion)

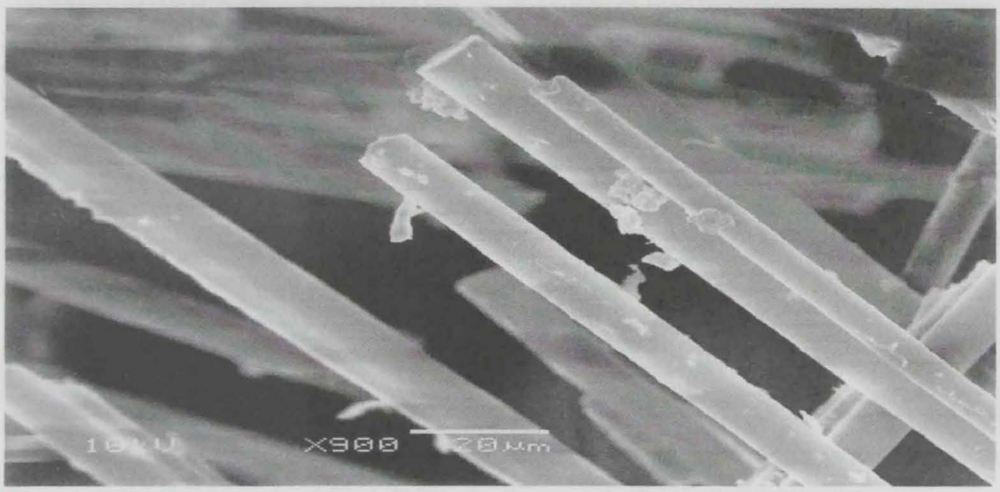

Figure 5.5: Fractured surface for a virgin sample (vacuum infusion)

Fractured samples obtained from the hybrid composite (Kevlar and carbon) were also investigated using the scanning electron microscope. Virgin samples were compared to immersed samples as shown in Figures 5.6 and 5.7.

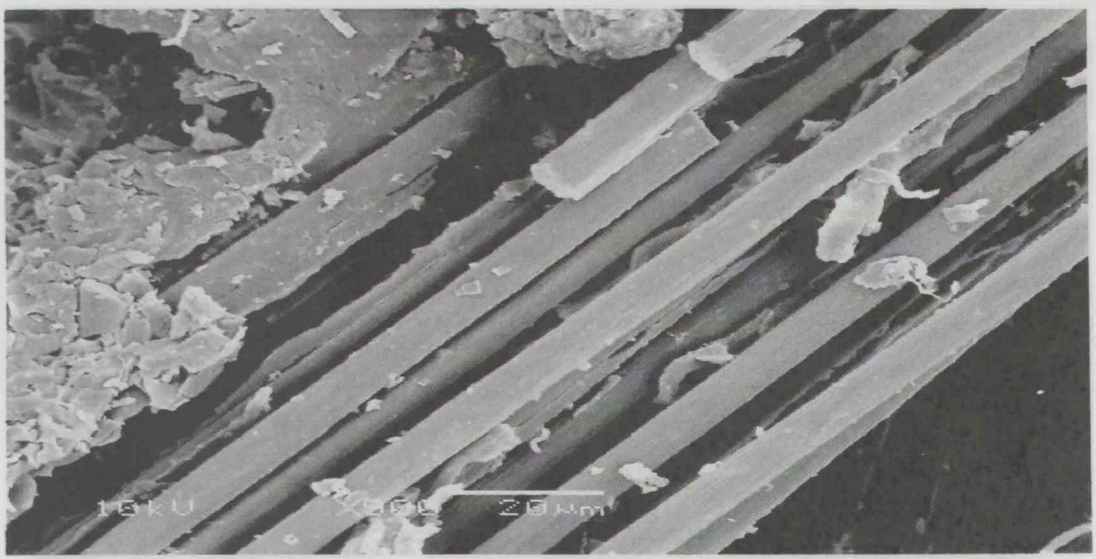

Figure 5.6: Fractured surface for a virgin hybrid composite (vacuum infusion)

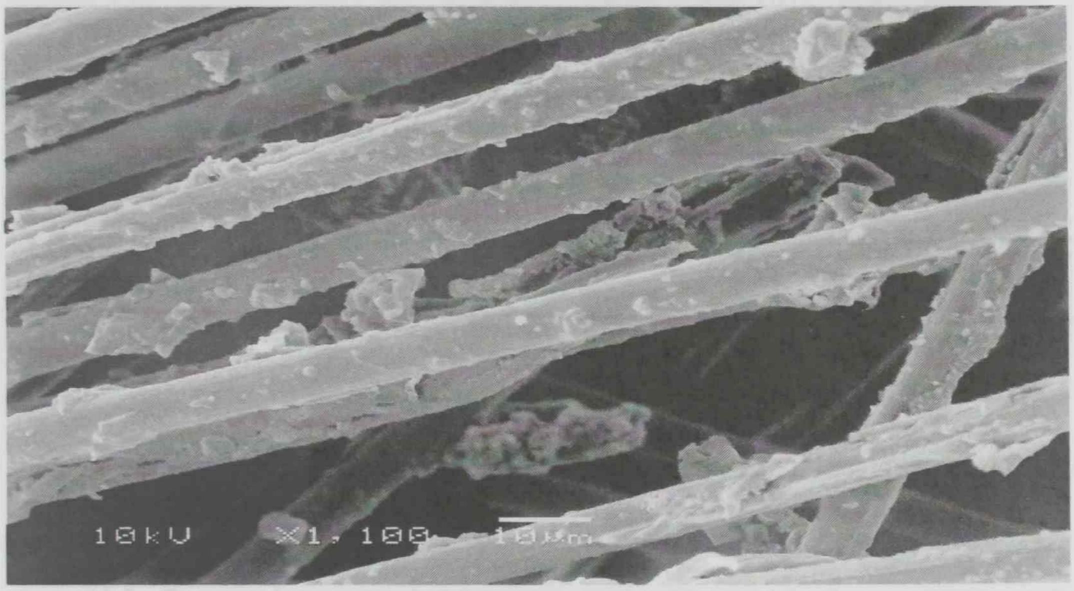

Figure 5.7: Fractured surface of an immersed hybrid composite (vacuum infusion)

When analyzing the fractured surfaces, it is clear that immersion results in water diffusion in the matrix thus affecting its strength and a softening of the matrix occurs, which yields large size areas fragments of the resin. This effect of matrix softening may result in the appearance of cracking between adjacent layers as shown in Figure 5.8.

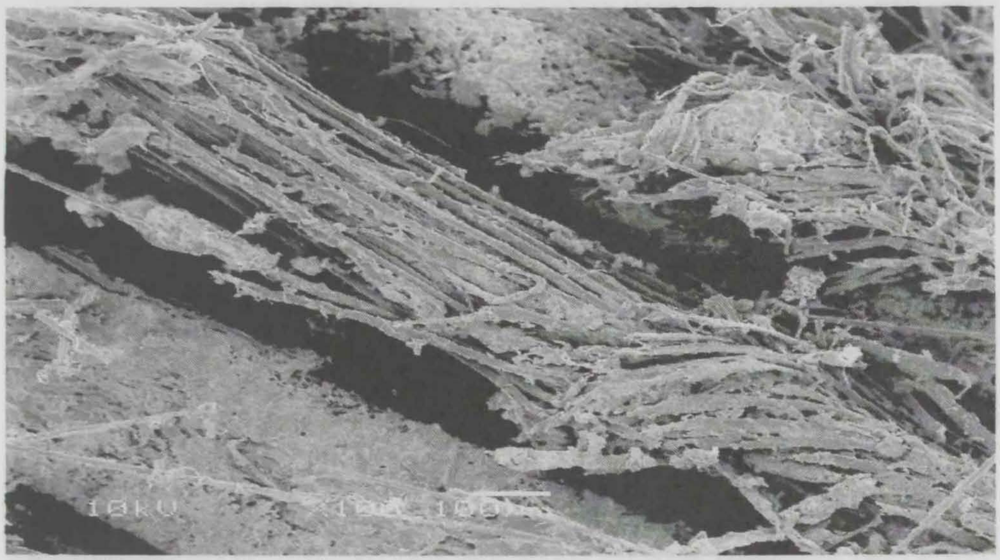

Figure 5.8: Layers cracking in the fractured immersed samples

Curing of composites samples at room temperature will not allow the samples to achieve full cure. As a consequence and this apply for samples produced using vinyl ester resin, leaching of the unreacted resin may take place while the samples are immersed in the physiological solution (Figures 5.9 and 5.10). This phenomenon may accelerate water absorption thus leading to the appearance of cracks in the resin interface surrounding the fibers (see Figure 5.1).

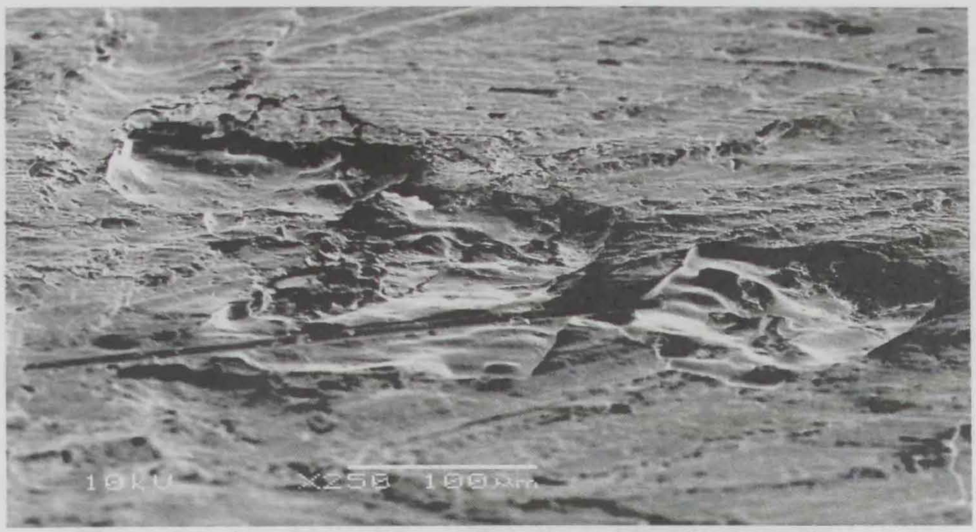

Figure 5.9: Leaching of the surface layer, hybrid composite

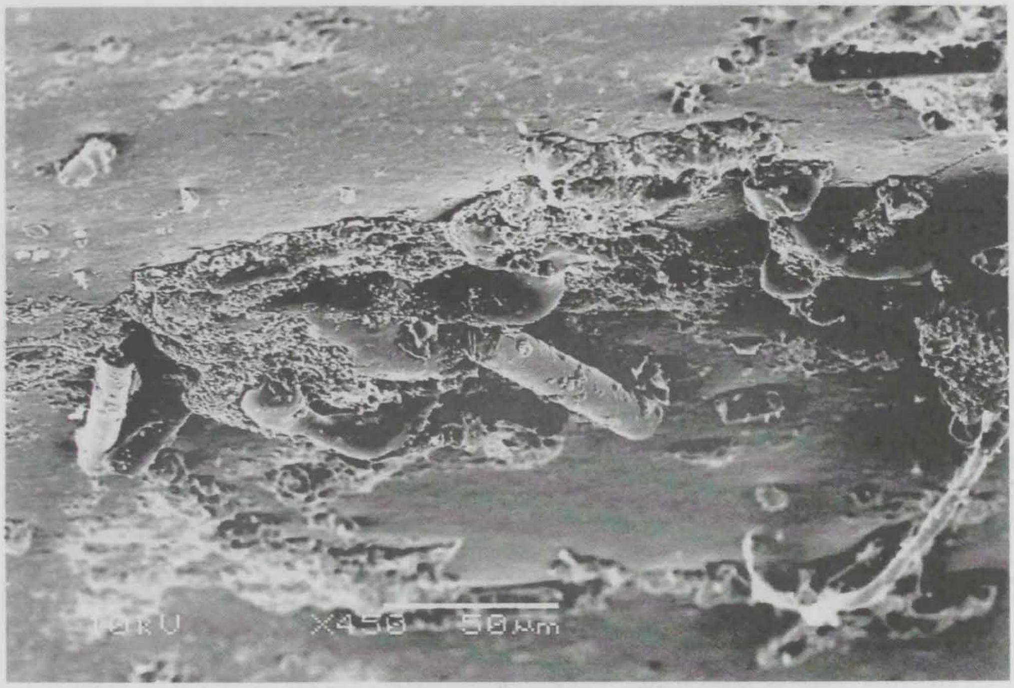

Figure 5.10: Leaching of the surface layer, Glass composite

5.3.2 Dynamic loading fracture

Composites specimens that were immersed for a period of six month in the physiological solution were subject to tensile fatigue testing and fractured surfaces were analyzed using scanning electron microscopy.

For specimens produced using glass fiber, it appears that two factors were affecting the performance of these specimens under fatigue testing. First of all, and this finding was similar to the one made for static loading fracture, moisture absorption of the resin will lead to increased softening thus explaining the appearance of micro-cracks (Figure 5.11). Secondly, the quality of the fiber resin interface is crucial when it comes to assess the long term performance of the composite. It is clear that the matrix loosening surrounding the fiber (Figure 5.12) is resulting from a poor interface, which is probably originated from micro-delamination between the fiber and the matrix.

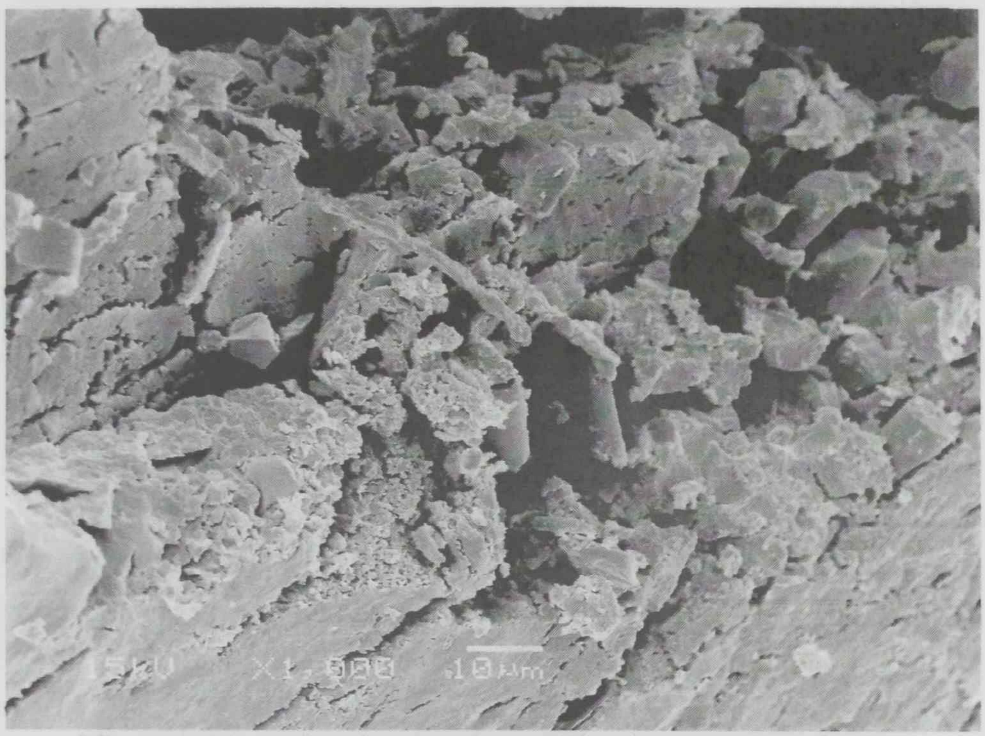

Figure 5.11 matrix micro-cracks resulting from matrix softening

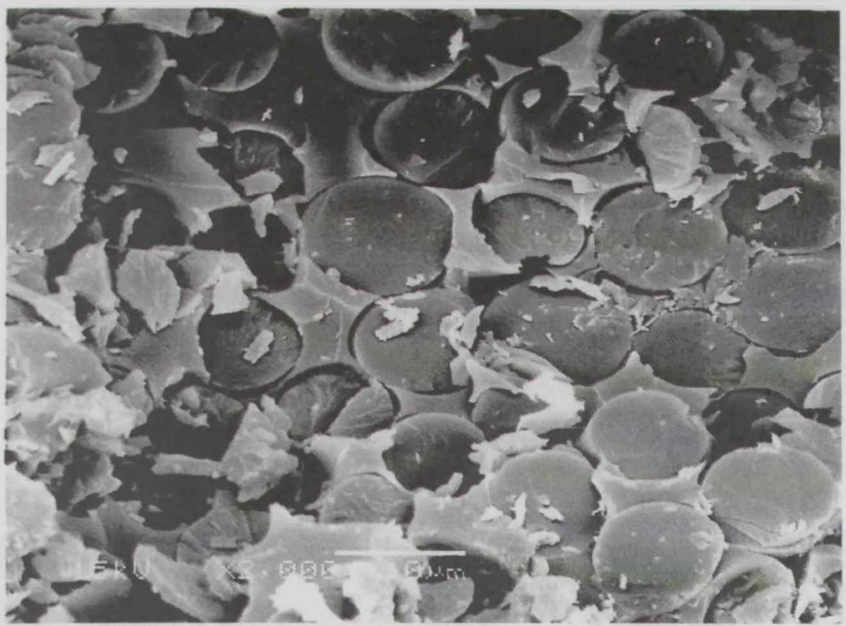

Figure 5.12 Matrix loosening surrounding the fiber

For hybrid specimens made out of carbon and aramid fibers, similar conclusion can be drawn for the main factors affecting the performance of these materials. For instance, softening that is taking place in the matrix, which is resulting from matrix diffusion, will lead to matrix fragmentation (Figure 5.13).

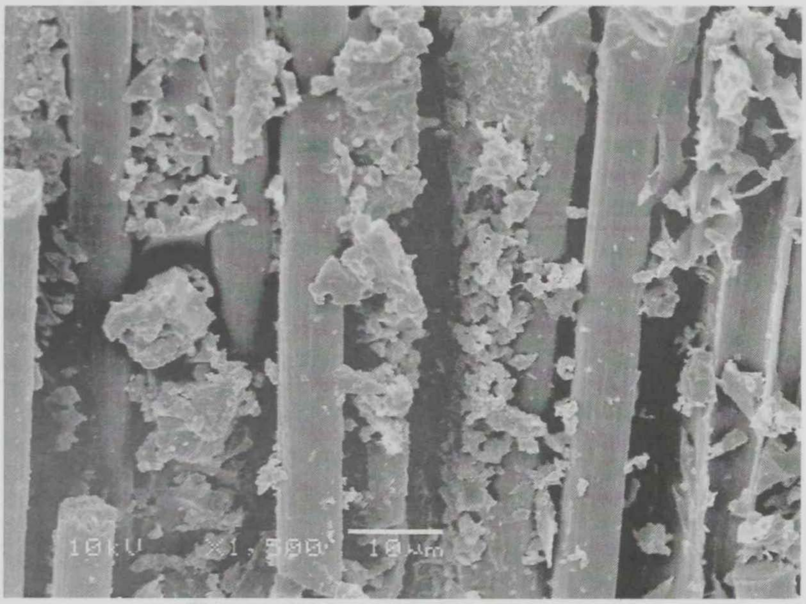

Figure 5.13 matrix fragmentation

For the fiber-matrix interface, although the quality of the interface is better than the one observed with glass fiber, it is still possible to observe some delamination appearing between the fiber and the matrix (Figure 5.14). Actually it was expected that the hybrid composite will result in a higher fatigue performance, however in order to take advantage of this performance, it is necessary to improve the adhesion between the fibers and the matrix.

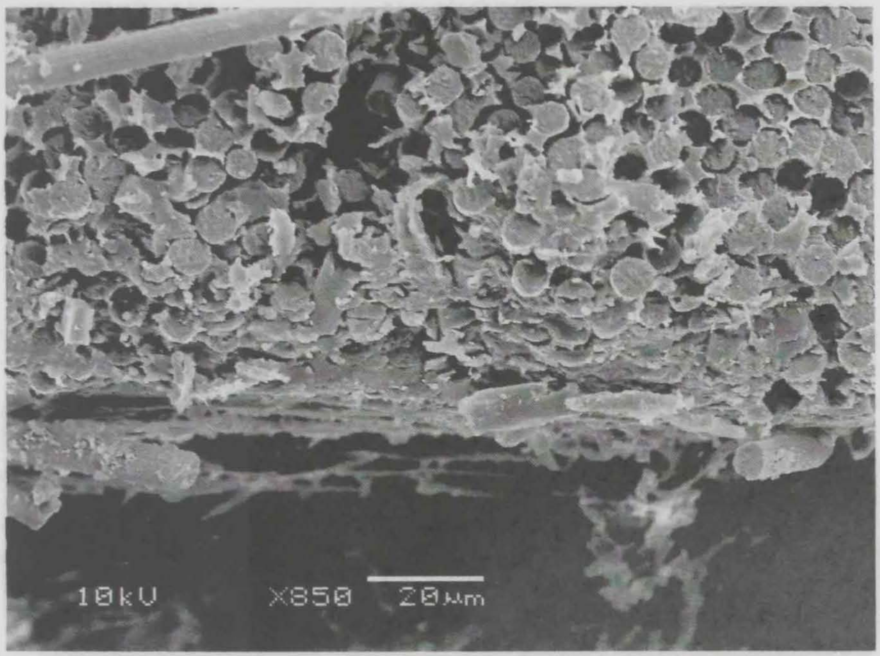

Figure 5.14. Fiber-matrix interface in the hybrid specimen.

Chapter Six

Conclusion and Recommendations

The main objective of this work was to investigate the performance of braided composites for the design of a hip prosthesis made from hybrid materials. Braided fabrics are known for their high mechanical performance, especially their high resistance to delamination. Furthermore, a hybrid material made of carbon fibers and aramid will feature the high strength of carbon fibers in addition to high impact resistance of aramid fibers.

Specimens were divided into three groups and each group contains eight specimens. Some of the specimens were kept immersed in a physiological solution for eight weeks, while others were used as virgin specimens. The reason for this immersion into the physiological solution was to compare the mechanical properties of the implanted composites with the virgin ones.

After reviewing the results and SEM images of the fractured specimens, the following observations can be drawn:

- The processing technique is very important factor, which can significantly affect the performance of the composite materials. For example, specimens undergoing enough curing cycle; normally will result in an increase of the mechanical properties. On the other hand, specimens immersed in the physiological solution showed some degradation in mechanical properties.
- Specimens made by hot press and vacuum infusion techniques showed failures due to matrix cracking and delamination. The cracking and delamination occurred as a result of water diffusion through the matrix, which resulted in poor bonding between the fiber and the matrix.

- Immersed specimens showed decrease in the mechanical properties due to water absorption within the matrix. Although this was not the case for glass fibers made by hot press technique, in which the mechanical degradation did not occur due to the lack of sufficient resin available in the fiber-matrix interface.
- Hybrid composite specimens made by vacuum infusion showed also failures due to matrix cracking and delamination as a result of water diffusion in the matrix.
- Uncured composite specimens caused leaching of the unreacted vinyl ester resin, which accelerated water absorption in the matrix thus leading to matrix cracking in the resin interface.
- Specimens tested under fatigue testing also showed delamination at the fiber-matrix interface. It is clear that in order to enhance the fatigue properties of these specimens, one needs to improve the adhesion between the fibers and the matrix. The fracture occurred as a result of moisture absorption of the resin, which led to increased softening and eventually to matrix cracking.
- Similar conclusion can be applied to the hybrid specimens under fatigue testing. For example, softening is taking place in the matrix, which will lead to matrix cracking.

Finally, it is important to stress that the objective of this work was twofold: first to investigate the performance of braided composites for the design of a hip prosthesis and second to assess the fatigue performance of hybrid composites. Braided composite were chosen in order to enhance the material resistance to delamination and hybrid composite made out of carbon and aramid to enhance the fatigue performance of the composite hip joint.

The resin system used did not contribute in enhancing the fatigue performance as expected. Actually, vinyl ester resin was chosen as an affordable material combining both the excellent performance of epoxy and relatively low cost of polyester. However, it seems that further work is needed in order to improve the adhesion to the fibers.

Through this work, it was possible to explore the advantages offered by a hybrid and braided composite and to compare different manufacturing methods and the effect of environmental testing on the performance of the materials. However, further developments are needed in order to assess the performance of these materials as the material of choice for hip joint replacement. These developments are concerned with the development of a manufacturing process. For instance, it appears that liquid composite molding processes such resin transfer molding and bladder molding could be considered as potential candidates. Also, it is important to develop a finite element model for the hip joint in order to simulate all possible loading situations. This will reduce drastically the time allocated for experimentation.

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Appendix A: Theoretical Results

Table 1: elastic properties of a unidirectional continuous fiber 0^{o} lamina for all cases

	Carbon / epoxy	
Longitudinal modulus		$E_{11} = 96.1$ GPa
Transverse modulus		$E_{22} = 4.80$ GPa
Major Poisson's ratio		$\nu_{12} = 0.262$
Minor Poisson's ratio		$\nu_{21} = 0.013$
Shear modulus		$G_{12} = 1.84$ GPa
	Carbon / vinyl ester	
Longitudinal modulus		$E_{11} = 96.2$ GPa
Transverse modulus		$E_{22} = 5.20$ GPa
Major Poisson's ratio		$\nu_{12} = 0.262$
Minor Poisson's ratio		$\nu_{21} = 0.014$
Shear modulus		$G_{12} = 2.00$ GPa
	Carbon / PEEK	
Longitudinal modulus		$E_{11} = 96.2$ GPa
Transverse modulus		$E_{22} = 5.18$ GPa
Major Poisson's ratio		$\nu_{12} = 0.324$
Minor Poisson's ratio		$\nu_{21} = 0.017$
Shear modulus		$G_{12} = 1.85$ GPa
	Carbon / aramid fibers and epoxy	
Longitudinal modulus		$E_{11} = 78.3$ GPa
Transverse modulus		$E_{22} = 4.79$ GPa
Major Poisson's ratio		$\nu_{12} = 0.284$
Minor Poisson's ratio		$\nu_{21} = 0.017$
Shear modulus		$G_{12} = 1.84$ GPa
	Carbon / aramid fibers and vinyl ester	
Longitudinal modulus		$E_{11} = 78.4$ GPa
Transverse modulus		$E_{22} = 5.19$ GPa
Major Poisson's ratio		$\nu_{12} = 0.284$
Minor Poisson's ratio		$\nu_{21} = 0.018$
Shear modulus		$G_{12} = 1.99$ GPa
	Carbon / aramid and PEEK	
Longitudinal modulus		$E_{11} = 78.4$ GPa
Transverse modulus		$E_{22} = 5.17$ GPa
Major Poisson's ratio		$\nu_{12} = 0.346$
Minor Poisson's ratio		$\nu_{21} = 0.022$
Shear modulus		$G_{12} = 1.84$ GPa

	Glass / aramid and epoxy	
Longitudinal modulus		$E_{11} = 38.1$ GPa
Transverse modulus		$E_{22} = 4.74$ GPa
Major Poisson’s ratio		$\nu_{12} = 0.284$
Minor Poisson’s ratio		$\nu_{21} = 0.035$
Shear modulus		$G_{12} = 1.82$ GPa
	Glass / aramid and vinyl ester	
Longitudinal modulus		$E_{11} = 38.3$ GPa
Transverse modulus		$E_{22} = 5.13$ GPa
Major Poisson’s ratio		$\nu_{12} = 0.284$
Minor Poisson’s ratio		$\nu_{21} = 0.038$
Shear modulus		$G_{12} = 1.97$ GPa
	Glass / aramid and PEEK	
Longitudinal modulus		$E_{11} = 38.3$ GPa
Transverse modulus		$E_{22} = 5.11$ GPa
Major Poisson’s ratio		$\nu_{12} = 0.346$
Minor Poisson’s ratio		$\nu_{21} = 0.046$
Shear modulus		$G_{12} = 1.83$ GPa

Table 2: elastic properties of a unidirectional continuous fiber (hybrid fabrics) angle-ply lamina for all cases

	Carbon fibers and epoxy at angle $\theta = 15^{o}$	
Longitudinal modulus		$E_{xx} = 22.9$ GPa
Transverse modulus		$E_{yy} = 4.65$ GPa
In-plane shear modulus		$G_{xy} = 2.15$ GPa
Poisson's ratio		$\nu_{xy} = 0.471$
Poisson's ratio		$\nu_{yx} = 0.095$
	Carbon fibers and epoxy at angle $\theta = 20^{o}$	
Longitudinal modulus		$E_{xx} = 15.0$ GPa
Transverse modulus		$E_{yy} = 4.58$ GPa
In-plane shear modulus		$G_{xy} = 2.43$ GPa
Poisson's ratio		$\nu_{xy} = 0.536$
Poisson's ratio		$\nu_{yx} = 0.163$
	Carbon fibers and epoxy at angle $\theta = 25^{o}$	
Longitudinal modulus		$E_{xx} = 10.8$ GPa
Transverse modulus		$E_{yy} = 4.55$ GPa
In-plane shear modulus		$G_{xy} = 2.80$ GPa

Poisson's ratio		$\nu_{xy} = 0.536$
Poisson's ratio		$\nu_{yx} = 0.225$
	Carbon fibers and vinyl ester at angle $\theta = 15^{o}$	
Longitudinal modulus		$E_{xx} = 24.5$ GPa
Transverse modulus		$E_{yy} = 5.04$ GPa
In-plane shear modulus		$G_{xy} = 2.34$ GPa
Poisson's ratio		$\nu_{xy} = 0.513$
Poisson's ratio		$\nu_{yx} = 0.105$
	Carbon fibers and vinyl ester at angle $\theta = 20^{o}$	
Longitudinal modulus		$E_{xx} = 16.1$ GPa
Transverse modulus		$E_{yy} = 4.97$ GPa
In-plane shear modulus		$G_{xy} = 2.63$ GPa
Poisson's ratio		$\nu_{xy} = 0.513$
Poisson's ratio		$\nu_{yx} = 0.163$
	Carbon fibers and vinyl ester at angle $\theta = 25^{o}$	
Longitudinal modulus		$E_{xx} = 11.69$ GPa
Transverse modulus		$E_{yy} = 4.93$GPa
In-plane shear modulus		$G_{xy} = 3.04$ GPa
Poisson's ratio		$\nu_{xy} = 0.532$
Poisson's ratio		$\nu_{yx} = 0.224$
	Carbon fibers and PEEK at angle $\theta = 15^{o}$	
Longitudinal modulus		$E_{xx} = 24.5$ GPa
Transverse modulus		$E_{yy} = 5.04$GPa
In-plane shear modulus		$G_{xy} = 2.34$ GPa
Poisson's ratio		$\nu_{xy} = 0.513$
Poisson's ratio		$\nu_{yx} = 0.105$
	Carbon fibers and PEEK at angle $\theta = 20^{o}$	
Longitudinal modulus		$E_{xx} = 16.1$ GPa
Transverse modulus		$E_{yy} = 4.97$GPa
In-plane shear modulus		$G_{xy} = 2.63$ GPa
Poisson's ratio		$\nu_{xy} = 0.531$
Poisson's ratio		$\nu_{yx} = 0.163$
	Carbon fibers and PEEK at angle $\theta = 25^{o}$	
Longitudinal modulus		$E_{xx} = 11.6$ GPa
Transverse modulus		$E_{yy} = 4.93$GPa
In-plane shear modulus		$G_{xy} = 3.04$ GPa

Poisson's ratio		$\nu_{xy} = 0.532$
Poisson's ratio		$\nu_{yx} = 0.224$
	Carbon / aramid and epoxy at angle $\theta = 15^o$	
Longitudinal modulus		$E_{xx} = 21.9$ GPa
Transverse modulus		$E_{yy} = 4.64$GPa
In-plane shear modulus		$G_{xy} = 2.15$ GPa
Poisson's ratio		$\nu_{xy} = 0.511$
Poisson's ratio		$\nu_{yx} = 0.108$
	Carbon / aramid and epoxy at angle $\theta = 20^o$	
Longitudinal modulus		$E_{xx} = 14.6$ GPa
Transverse modulus		$E_{yy} = 4.58$GPa
In-plane shear modulus		$G_{xy} = 2.42$ GPa
Poisson's ratio		$\nu_{xy} = 0.529$
Poisson's ratio		$\nu_{yx} = 0.165$
	Carbon / aramid and epoxy at angle $\theta = 25^o$	
Longitudinal modulus		$E_{xx} = 10.6$ GPa
Transverse modulus		$E_{yy} = 4.55$GPa
In-plane shear modulus		$G_{xy} = 2.79$ GPa
Poisson's ratio		$\nu_{xy} = 0.531$
Poisson's ratio		$\nu_{yx} = 0.226$
	Carbon / aramid and vinyl ester at angle $\theta = 15^o$	
Longitudinal modulus		$E_{xx} = 23.3$ GPa
Transverse modulus		$E_{yy} = 5.03$GPa
In-plane shear modulus		$G_{xy} = 2.33$ GPa
Poisson's ratio		$\nu_{xy} = 0.506$
Poisson's ratio		$\nu_{yx} = 0.109$
	Carbon / aramid and vinyl ester at angle $\theta = 20^o$	
Longitudinal modulus		$E_{xx} = 15.7$ GPa
Transverse modulus		$E_{yy} = 4.96$GPa
In-plane shear modulus		$G_{xy} = 2.62$ GPa
Poisson's ratio		$\nu_{xy} = 0.526$
Poisson's ratio		$\nu_{yx} = 0.166$
	Carbon / aramid and vinyl ester at angle $\theta = 25^o$	
Longitudinal modulus		$E_{xx} = 11.4$ GPa
Transverse modulus		$E_{yy} = 4.93$GPa
In-plane shear modulus		$G_{xy} = 3.01$ GPa

Poisson's ratio		$\nu_{xy} = 0.528$
Poisson's ratio		$\nu_{yx} = 0.226$
	Carbon / aramid and PEEK at angle $\theta = 15^o$	
Longitudinal modulus		$E_{xx} = 22.0$ GPa
Transverse modulus		$E_{yy} = 4.95$GPa
In-plane shear modulus		$G_{xy} = 2.18$ GPa
Poisson's ratio		$\nu_{xy} = 0.549$
Poisson's ratio		$\nu_{yx} = 0.123$
	Carbon / aramid and PEEK at angle $\theta = 20^o$	
Longitudinal modulus		$E_{xx} = 14.7$ GPa
Transverse modulus		$E_{yy} = 4.85$GPa
In-plane shear modulus		$G_{xy} = 2.46$ GPa
Poisson's ratio		$\nu_{xy} = 0.565$
Poisson's ratio		$\nu_{yx} = 0.185$
	Carbon / aramid and PEEK at angle $\theta = 25^o$	
Longitudinal modulus		$E_{xx} = 10.7$ GPa
Transverse modulus		$E_{yy} = 4.78$GPa
In-plane shear modulus		$G_{xy} = 2.87$ GPa
Poisson's ratio		$\nu_{xy} = 0.565$
Poisson's ratio		$\nu_{yx} = 0.251$
	Glass / aramid and epoxy at angle $\theta = 15^o$	
Longitudinal modulus		$E_{xx} = 17.5$ GPa
Transverse modulus		$E_{yy} = 4.61$ GPa
In-plane shear modulus		$G_{xy} = 2.11$ GPa
Poisson's ratio		$\nu_{xy} = 0.455$
Poisson's ratio		$\nu_{yx} = 0.120$
	Glass / aramid and epoxy at angle $\theta = 20^o$	
Longitudinal modulus		$E_{xx} = 12.7$ GPa
Transverse modulus		$E_{yy} = 4.55$ GPa
In-plane shear modulus		$G_{xy} = 2.35$ GPa
Poisson's ratio		$\nu_{xy} = 0.486$
Poisson's ratio		$\nu_{yx} = 0.173$
	Glass / aramid and epoxy at angle $\theta = 25^o$	
Longitudinal modulus		$E_{xx} = 9.74$ GPa
Transverse modulus		$E_{yy} = 4.52$ GPa
In-plane shear modulus		$G_{xy} = 2.67$ GPa

Poisson's ratio		$\nu_{xy} = 0.497$
Poisson's ratio		$\nu_{yx} = 0.230$
	Glass / aramid and vinyl ester at angle $\theta = 15^{o}$	
Longitudinal modulus		$E_{xx} = 18.3$ GPa
Transverse modulus		$E_{yy} = 4.98$ GPa
In-plane shear modulus		$G_{xy} = 2.28$ GPa
Poisson's ratio		$\nu_{xy} = 0.448$
Poisson's ratio		$\nu_{yx} = 0.121$
	Glass / aramid and vinyl ester at angle $\theta = 20^{o}$	
Longitudinal modulus		$E_{xx} = 13.5$GPa
Transverse modulus		$E_{yy} = 4.92$GPa
In-plane shear modulus		$G_{xy} = 2.54$ GPa
Poisson's ratio		$\nu_{xy} = 0.440$
Poisson's ratio		$\nu_{yx} = 0.171$
	Glass / aramid and vinyl ester at angle $\theta = 25^{o}$	
Longitudinal modulus		$E_{xx} = 10.4$GPa
Transverse modulus		$E_{yy} = 4.89$GPa
In-plane shear modulus		$G_{xy} = 2.88$ GPa
Poisson's ratio		$\nu_{xy} = 0.593$
Poisson's ratio		$\nu_{yx} = 0.231$
	Glass / aramid and PEEK at angle $\theta = 15^{o}$	
Longitudinal modulus		$E_{xx} = 17.5$GPa
Transverse modulus		$E_{yy} = 4.91$GPa
In-plane shear modulus		$G_{xy} = 2.13$ GPa
Poisson's ratio		$\nu_{xy} = 0.500$
Poisson's ratio		$\nu_{yx} = 0.139$
	Glass / aramid and PEEK at angle $\theta = 20^{o}$	
Longitudinal modulus		$E_{xx} = 12.8$GPa
Transverse modulus		$E_{yy} = 4.81$GPa
In-plane shear modulus		$G_{xy} = 2.39$ GPa
Poisson's ratio		$\nu_{xy} = 0.527$
Poisson's ratio		$\nu_{yx} = 0.198$
	Glass / aramid and PEEK at angle $\theta = 25^{o}$	
Longitudinal modulus		$E_{xx} = 9.82$GPa
Transverse modulus		$E_{yy} = 4.74$GPa
In-plane shear modulus		$G_{xy} = 2.75$ GPa

Poisson's ratio	$\nu_{xy} = 0.537$
Poisson's ratio	$\nu_{yx} = 0.259$

Appendix B: Statistics for THR conducted in the U.A.E.

Table 1: Statistic for (THR)- Al-Qassimi Hospital- Sharjah

NO	Age	Sex	Cause of THR	Date of THR	Follow-up
1	63	M	Osteoarthritis	1993	OK-no infection-no metal fatigue- no loosening
2	52	M	Osteoarthritis	2001	OK
3	77	F	Fracture	2002	OK
4	25	M	Fracture	2002	OK
5	28	F	Avascular necrosis (A.N)	2001	OK
6	37	F	Fracture	2001	OK
7	26	F	Avascular necrosis	2001	OK
8	57	F	Loosening of previous THR	2002	OK
9	44	M	Avascular necrosis	2001	OK
10	21	F	Avascular necrosis (Bilateral)	2001	OK

Table 2: Statistic for (THR)- Saqer Hospital- Ras Al-Khaima

NO	Age	Sex	Cause of THR	Date of THR	Follow-up
1	55	F	Avascular necrosis (Bilateral)	1997	Smooth
2	55	F	Avascular necrosis (Bilateral)	1997	Smooth
3	65	M	Osteoarthritis	1998	Smooth
4	80	F	Osteoarthritis	1999	Superficial Infection
5	65	M	Osteoarthritis	2000	Smooth
6	60	M	Old Trauma	2000	Smooth
7	60	M	Avascular necrosis (Bilateral)	2000	Smooth
8	70	M	Old Trauma	2001	Smooth

Table 3: Statistic for (THR)- Tawam Hospital- Al-Ain

NO	Age	Sex	Cause of THR	Date of THR	Follow-up
1	25	F	Avascular necrosis	3-2002	Ok-no Complication
2	36	M	Avascular necrosis	5-2002	Ok-no Complication
3	46	F	Avascular necrosis	1-2000	Ok-no Complication
4	30	M	Avascular necrosis	3-1998	Aseptic loosening
5	42	M	Avascular necrosis	8-2002	Ok-no Complication
6	65	M	Avascular necrosis	8-2000	Died two days after surgery
7	54	F	Osteoarthritis	7-9-2002	Ok-no Complication

Table 4: Statistic for (THR)- Al-Ain Hospital- Al-Ain

NO	Age	Sex	Cause of THR	Date of THR	Follow-up
1	48	F	Secondary Osteoarthritis Accident	31-7-2002	Ok-no Complication

Table 5: Statistic for (THR)- Al-Magraq Hospital- Abu-Dhabi

NO	Age	Sex	Cause of THR	Date of THR	Follow-up
1	28	M	Ankylosing Spondylitis	2001	Ok-no infection & no loosening
2	40	M	Avascular necrosis (Left hip)	2000	Occasional pain-no infection & no loosening
3	39	M	Avascular necrosis (severe on Right hip)	2000	Ok-no infection & no loosening
4	48	M	Fracture dislocation left hip	1997	No infection & no loosening
5	35	F	Osteoarthritis Right hip	1997	No infection & no loosening
6	43	F	Rheumatiod arthritis	2000	Ok-no infection & no loosening
7	60	M	Advanced Osteoarthritis left hip	1998	Ok-no infection & no loosening
8	42	M	Bilateral neglected CDH	2000	Ok-no infection & no loosening
9	50	F	Osteoarthritis Right hip	1999	Ok-no infection & no loosening
10	30	M	Fracture Right femur	1999	Ok-no infection & no loosening

Table 6: Statistic for (THR)- American Hospital- Dubai

Age	Sex	Cause of THR	Date of THR	Follow-up
65	F	Osteoarthritis	1998	Ok-no infection & no loosening
62	F	Osteoarthritis	1998	OK
42	M	Avascular necrosis	1998	Patient died in car accident
68	F	Osteoarthritis (right hip)	1998	OK
76	F	Osteoarthritis	1998	OK
32	M	Rheumatiod arthritis (bilateral hip)	1999	OK
28	M	Juvenil rheumatoid arthritis (bilateral hip)	1999	OK
58	M	Osteoarthritis (right hip)	1999	Hip revised in2002 due to loosening, patient recovering
32	M	Perthes' disease	1999	OK
41	M	Avascular necrosis (left hip)	1999	OK
67	M	Osteoarthritis	1999	OK
66	M	Fracture hip	1999	Infection developed
73	F	Fracture hip	1999	OK
79	M	Fracture hip	1999	OK
74	F	Fracture hip	1999	OK
52	M	Avascular necrosis	2000	OK
59	M	Osteoarthritis	2000	OK
68	M	Fracture hip	2000	OK
35	M	Avascular necrosis	2000	OK
28	F	Fracture hip	2000	OK
62	M	Osteoarthritis	2000	OK
78	F	Fracture hip	2000	OK
72	F	Fracture hip	2000	OK
49	F	Avascular necrosis (left hip)	2000	OK
47	F	Revision of failed hip done in 1994 for fracture	2000	OK
79	M	Fracture hip	2001	OK
61	F	Osteoarthritis	2001	OK
86	M	Fracture hip	2001	OK
38	M	Fracture hip	2001	OK
65	F	Osteoarthritis	2001	OK
66	F	Fracture hip	2001	OK
78	M	Osteoarthritis	2001	OK
74	F	Fracture hip	2001	OK
90	F	Fracture hip	2001	OK
54	M	Avascular necrosis	2001	OK
61	F	Osteoarthritis	2001	OK

Table 7: Statistic for (THR)- Dubai Hospital- Dubai

NO	Age	Sex	Cause of THR	Date of THR	Follow-up
1	50	F	Rheumatiod arthritis	15/2/1995	Dislocation, revision
2	61	M	Osteoarthritis, diabetes	18/3/1995	Infection, Loosening acetabulum
3	39	F	Rheumatiod arthritis	8/11/1995	Ok, no loosening, no infection
4	72	F	Old fracture neck of femur	24/4/1996	Dislocation, revision of acetabulum
5	61	M	Osteoarthritis	19/6/1996	Ok, no loosening, no infection
6	55	M	Osteoarthritis	30/10/1996	Ok, no loosening, no infection
7	54	F	Rheumatiod arthritis	18/10/1997	Ok, no loosening, no infection
8	44	F	Rheumatiod arthritis	3/4/1998	Ok, no loosening, no infection
9	75	M	Osteoarthritis	12/8/1998	Dislocation, revision
10	23	F	S.L.E.	29/5/1999	Ok, no loosening, no infection
11	42	M	Old fracture neck of femur	14/7/1999	Ok, no loosening, no infection
12	61	M	Osteoarthritis	20/10/1999	Ok, no loosening, no infection
13	46	M	Old fracture neck of femur	26/1/2000	Loosening of femoral component
14	59	M	Osteoarthritis	22/7/2000	Ok, no loosening, no infection
15	30	F	Epiphyseal dysplasia	7/10/2000	Ok, no loosening, no infection
16	45	M	AV.N. head of femur	8/11/2000	Ok, no loosening, no infection
17	16	F	Rheumatiod arthritis	13/6/2001	Ok, no loosening, no infection
18	30	F	Epiphyseal dysplasia	17/10/2001	Ok, no loosening, no infection
19	50	M	Osteoarthritis	20/10/2001	Ok, no loosening, no infection
20	16	F	Rheumatiod arthritis	3/11/2001	Ok, no loosening, no infection
21	33	F	Rheumatiod arthritis	10/7/2002	Ok, no loosening, no infection
22	20	F	Rheumatiod arthritis	28/9/2002	Ok, no loosening, no infection

C: Immersion of the specimens in the physiological solution

Weight gain for glass fiber specimen made by vacuum infusion after immersion in the ical solution.

09/04/02	23/04/02	07/05/02	21/05/02	04/06/02	18/06/02	02/07/02	09/07/02
9.98	10	10.03	10.05	10.06	10.07	10.08	10.08
9.84	9.87	9.9	9.92	9.94	9.96	9.98	9.99
9.71	9.74	9.77	9.79	9.81	9.83	9.85	9.86
8.47	8.49	8.5	8.51	8.52	8.53	8.54	8.54
8.8	8.81	8.83	8.85	8.86	8.87	8.88	8.89
8.91	8.93	8.94	8.95	8.96	8.97	8.98	8.98
8.7	8.73	8.75	8.77	8.79	8.81	8.82	8.83

Weight gain for glass fiber specimen made by hot press after immersion in the ical solution.

09/04/02	23/04/02	07/05/02	21/05/02	04/06/02	18/06/02	02/07/02	09/07/02
7.24	7.29	7.34	7.36	7.38	7.39	7.4	7.41
7.2	7.25	7.29	7.33	7.35	7.37	7.39	7.41
7.71	7.76	7.81	7.85	7.88	7.9	7.91	7.92
7.6	7.65	7.7	7.73	7.75	7.77	7.78	7.78
7.16	7.23	7.29	7.34	7.38	7.4	7.41	7.42
7.34	7.48	7.59	7.6	7.61	7.62	7.63	7.63
7.07	7.19	7.21	7.23	7.25	7.26	7.27	7.27

eight gain for carbon / aramid fiber specimen made by vacuum infusion after immersion siological solution.

09/04/02	23/04/02	07/05/02	21/05/02	04/06/02	18/06/02	02/07/02	09/07/02
3.29	3.31	3.32	3.33	3.35	3.37	3.39	3.41
3.08	3.12	3.14	3.16	3.18	3.2	3.21	3.21
3.29	3.31	3.34	3.36	3.38	3.4	3.41	3.41
3.21	3.26	3.28	3.29	3.3	3.31	3.32	3.33
3.2	3.25	3.27	3.29	3.29	3.29	3.29	3.29
3.26	3.29	3.31	3.32	3.34	3.36	3.37	3.38
3.13	3.17	3.19	3.2	3.21	3.21	3.22	3.22

x D: Sample measurement dimensions for tested specimens

.: Measurement dimensions for carbon / aramid fiber specimen made by vacuum infusion.

imen No.	Thickness (mm)	Length (mm)	Width (mm)
1	1.3	80	19.9
2	1.24	80	19.48
3	1.2	80	20.36
4	1.22	80	20.18
5	1.3	80	20.29
6	1.26	80	19.97
7	1.13	80	18.99
8	1.18	80	20.17

:: Measurement dimensions for glass fiber specimen made by vacuum infusion.

imen No.	Thickness (mm)	Length (mm)	Width (mm)
1	2.87	80	20.39
2	2.9	80	19.41
3	2.98	80	19.44
4	2.75	80	19.8
5	2.78	80	20.59
6	2.74	80	20.61
7	2.77	80	20.26
8	2.71	80	19.13

: Measurement dimensions for glass fiber specimen made by hot press.

imen No.	Thickness (mm)	Length (mm)	Width (mm)
1	2.37	80	19.38
2	2.39	80	19.15
3	2.43	80	20.26
4	2.34	80	19.62
5	2.35	80	19.51
6	2.37	80	20.55
7	2.35	80	19.53
8	2.34	80	20.51

Glossary of terms

A

A-stage: An early stage of polymerization of thermosetting resins in which the material is still soluble in certain liquids and fusible.

Accelerator: Chemical additive that hastens cure or chemical reaction.

Acetabulum: Either of the two deep sockets, one on each side of the hip bone, into which the head of the thigh bone (femur) fits.

Addition: Polymerization reaction in which no byproducts are formed.

Additives: Ingredients mixed into resin to improve properties.

Adhesive: Substance applied to mating surfaces to bond them together by surface attachment.

Amorphous: Polymers with no crystalline component.

Angle-ply laminate: Any balanced laminate consisting of plies at angles of plus and minus theta, where theta is an acute angle with the principal laminate axis.

Ankylosing spondylitis: Is a rheumatic disease involving the backbone and sacroiliac joints.

Anisotropic: Not isotropic. Exhibiting different properties when tested along axes in different directions within the material.

Aramid: Aromatic polyamide fibers. (Often referred to as Kevlar, DuPont's trademark.)

Arthritis: Inflammation of one or more joints, characterized by swelling, redness, of the under-lying skin, pain, and restriction of motion.

Arthroplasty: Surgical remodeling of a diseased joint.

Articulation: (In anatomy) the point or type of contact between two bones.

Avascular: Lacking blood vessels or having a poor blood supply. The term is usually used with reference to cartilage.

B

B-stage: Intermediate stage in the polymerization reaction of some thermosets in which the material softens with heat and is plastic and fusible but does not entirely dissolve or fuse. The resin of an uncured prepreg or premix is usually in this state.

Bag molding: Molding technique in which the composite structure is placed in a rigid mold and covered with a flexible impermeable layer of film and the edges sealed, followed by consolidation and/or curing with pressure applied by vacuum, autoclave, press or inflation of the bag.

Benign tumor: Describing a tumor that does not invade and destroy the tissues in which it originates or spread to distant sites in the body, i.e. a tumor that is not cancerous.

Bismaleimide (BMI): Type of thermoset polyimide that cures by an additional reaction, thus avoiding formation of volatiles. Exhibits temperature capabilities between those of epoxy and polyimide.

Braiding: Textile process that intertwines into a pattern three or more strands, yarns or tapes, typically into a tubular shape.

Bundle: General term for a collection of essentially parallel filaments.

C

C-stage: Final step in the cure of a thermoset resin, resulting in irreversible hardening and insolubility.

Calcar: It is the projection in the medial wall of the lateral ventricle of the brain.

Carbon fiber: Reinforcing fiber produced by the pyrolysis of an organic precursor fiber, such as PAN, rayon or pitch, in an inert environment at temperatures above 1,800°F. The term carbon is often used interchangeably with the term graphite, but the fibers differ. Carbon fibers are typically carbonized at about 2,400°F and contain 93 percent to 95 percent carbon. Carbon fibers can be converted to graphite fibers by graphitization at 3,450°F to 4,500°F, after which they contain more than 99 percent elemental carbon. Carbon fibers are known for their lightweight, high strength and high stiffness.

Carbon/carbon: Composite of carbon fiber in a carbon matrix.

Catalyst: Substance that promotes or controls curing of a compound without being consumed in the reaction. (See also hardener.)

Composite: Three-dimensional combination of at least two materials differing in form or composition, with a distinct interface separating the components. Composite materials are usually manmade and created to obtain properties that cannot be achieved by any of the components acting alone.

Compression molding: Technique for molding thermoset plastics in which a part is shaped by placing the fiber and resin into an open mold cavity, closing the mold, and applying heat and pressure until the material has cured or achieved its final form.

Compressive strength: Resistance to a crushing or buckling force, the maximum compressive load a specimen sustains divided by its original cross-sectional area.

Condensation: Polymerization reaction in which simple by-products (for example, water) are released.

Consolidation: Processing step that compresses fiber and matrix to reduce voids and achieve a particular density.

Continuous filament: Individual, small-diameter reinforcement that is flexible and indefinite in length.

Continuous roving: Large bundle of parallel filaments coated with sizing, gathered together into single or multiple strands, and wound into a cylindrical package. May be used to provide continuous reinforcement in woven roving, filament winding, pultrusion, prepregs, or high-strength molding compounds (may also be used chopped).

Cross-laminated: Laminated with some of the layers oriented at one or more angles to the other layers with respect to the principal laminate axis.

Cross-linking: Polymerization reactions that branch out from the main molecular chain to form a networked pattern of chemical links.

Crystalline: Having a molecular structure in which the atoms are arranged in an orderly, three-dimensional pattern.

Cure: To change the physical properties of a material irreversibly by chemical reaction via heat and/or catalysts, with or without pressure.

Cure temperature: Temperature at which a material attains final cure.

Curing agent: Catalytic or reactive agent that brings about polymerization when added to a resin.

D

Damage tolerance: Measure of the ability of structures to retain load-carrying capability after exposure to sudden loads (for example, ballistic impact).

Debond: Deliberate separation of a bonded joint or interface, usually for repair or rework purposes. (See also disbond.)

Delamination: Separation of plies in a laminate due to adhesive failure. This may be local or may cover a large area. Also includes the separation of layers of fabric from the core structure.

Drape: The ability of prepreg to conform to the shape of a contoured surface.

E

E-glass: Denotes "electrical glass," so called because of its high electrical resistivity. Refers to borosilicate glass fibers most often used in conventional polymer matrix composites.

Elasticity: The property of materials to recover immediately their original size and shape when load is removed after deformation.

Elongation: The fractional increase in length of a material loaded in tension. When expressed as a percentage of the original length, it is called percent elongation.

Epoxy: Thermoset polymer containing one or more epoxide groups, curable by reaction with amines or other compounds.

Exotherm: Heat released during a chemical reaction. Uncontrolled exotherm can lead to extreme heat build up and possibly violent explosion.

F

Fabric: Planar textile. Also known as cloth.

Fabric, woven: Planar textile constructed by interlacing in a weaving process.

Fabrication: Process of making a composite part or tool.

Fascia: Connective tissue forming membranous layers of variable thickness in all regions of the body.

Fatigue: Failure or deterioration of a material's mechanical properties as a result of repeated cyclic loading or deformation over time.

Fatigue strength: Maximum cyclical stress withstood for a given number of cycles before a material fails. The residual strength after being subjected to fatigue loading.

Femoral: Of relating to the thigh or to the femur.

Fiber: One or more filaments in an ordered assemblage.

Fiber content: Amount of fiber present in a composite expressed either as a percent by weight or percent by volume. Also sometimes stated as a fiber volume fraction.

Fiber orientation: Direction of fiber alignment in a non woven or mat laminate wherein most of the fibers are placed in the same direction to afford greater strength in that direction.

Fiber-reinforced plastics (FRP): General term used for a polymer-matrix composite that is reinforced with cloth, mat, strands or any other fiber form. Often used to designate mid-range, glass-fiber reinforced composites.

Filament: Polycrystalline or amorphous individual fiber unit with a length-to-diameter ratio greater than one. The minimum diameter of a filament is not limited, but the maximum diameter may not exceed 0.010 inches. Filaments greater than about 0.002 inches in diameter are often referred to as wires.

Finite element analysis: Process of selecting the optimum combination of materials in a composite based on computational modeling and analysis.

Flexural modulus: Ratio, within the elastic limit, of the applied stress on a test sample in flexure to the corresponding strain in the outermost fibers of the sample.

Flexural strength: Strength of a material in bending, usually expressed in force per unit area, as the stress of a bent test sample at the instant of failure.

Fracture: Rupture of the surface of a laminate due to external or internal forces; may or may not result in complete separation.

Fracture toughness: Measure of the damage tolerance of a material containing initial flaws or cracks.

Fusion: (In surgery) the joining together of two structures.

G

Gel time: Period of time from initial mixing of liquid reactants to the point when gelation occurs as defined by a specific test method.

Glass transition: Reversible change in an amorphous polymer between a viscous condition and a hard, relatively brittle condition.

Glass-transition temperature (Tg): Approximate temperature at which increased molecular mobility results in significant changes in properties of a cured resin. The measured value of Tg can vary, depending on the test method.

Graphitization: Process of pyrolysis at very high temperatures (up to 5,400°F) that converts carbon to its crystalline allotropic form.

Graphite fibers: Carbon fiber that has been graphitized by heating and stretching at temperatures above 3,000°F.

H

Hardener: Substance used to promote or control curing action by participating in and being consumed by the cure reaction. (See also catalyst.)

Heat: Term used colloquially to indicate any temperature above ambient (room) temperature to which a part or material is or will be subjected.

Heat-distortion temperature (HDT): Temperature at which deflection occurs under specified temperature and stated load.

High-performance composites: Composites offering properties better than conventional structural metals, typically on a strength-to-weight or stiffness-to-weight basis. Such composites use continuous, oriented fibers in polymer, metal or ceramic matrices to achieve their superior properties.

Hybrid composite: Composite containing at least two distinct types of matrix or reinforcement. The matrix or reinforcement types can be distinct because of their physical properties, mechanical properties, material form and/or chemical composition.

I

Impact strength: A material's ability to withstand shock loading as measured by fracturing a specimen.

Impregnate - To saturate the voids and interstices of a reinforcement with a resin.

Interface - Surface between two materials: in glass fibers, for instance, the area at which the glass and sizing meet; in a laminate, the area at which the reinforcement and laminating resin meet.

Interlaminar: Existing or occurring between two or more adjacent laminae in a laminate.

Interlaminar shear: Shearing force that produces displacement between two laminae along the plane of their interface.

Intralaminar: Existing or occurring within a single lamina in a laminate.

Isotropic: Fiber directionality with uniform properties in all directions, independent of the direction of applied load.

K

Kevlar: Trademark of DuPont for high-performance para-aramid fibers used as reinforcements.

Knit: Textile process that interlocks, in a specific pattern, loops of yarn by means of needles or wires.

L

Lamina - Subunit of a laminate consisting of one or more adjacent plies of the same material with identical orientation.

Laminate - Any fiber- or fabric-reinforced composite consisting of laminae with one or more orientations with respect to some reference direction.

M

Macrophage: A large scavenger cell present in connective tissue and many major organs and tissues, including the bone marrow, spleen, lymph, nodes, liver, and the central nervous system.

Malignant tumor: Describing a tumor that invades and destroys the tissue in which it originates and can spread to other sites in the body via the bloodstream and lymphatic system.

Matrix: Material in which reinforcing fiber of a composite is imbedded: polymer, metal or ceramic.

Matrix content: Amount of matrix present in a composite expressed either as a percent by weight or percent by volume. For polymer-matrix composites this is the resin content. (See also fiber content.)

Metal-matrix composites (MMC): Continuous carbon, silicon carbide, or ceramic fibers embedded in a metallic matrix material.

Micro cracking: Microscopic cracks formed in composites when thermal stresses locally exceed the strength of the matrix.

Modulus: Measure of the ratio of applied load (stress) to the resultant deformation of a material. May be represented by a number or in descriptive terms as low, intermediate, high or ultrahigh. (See also stiffness, Young's modulus.)

Moisture absorption: Pickup of water vapor from the air by a material. Refers to vapor withdrawn from the air only as distinguished from water absorption, which is weight gain due to the absorption of water by immersion.

O

Osteoarthritis: a disease of joint cartilage, associated with secondary changes in the under-lying bone, which may ultimately cause pain and impair the function of the affected joint.

Osteolysis: Dissolution of bone through disease, commonly by infection or loss of the blood supply (ischaemia) to the bone.

Osteotomy: A surgical operation to cut a bone into two parts, followed by realignment of ends to allow healing.

P

Pagets' disease: A chronic disease of bones, occurring in elderly and most frequently affecting the skull, backbone, pelvis, and long bones.

Phenolic resin: Thermosetting resin produced by a condensation reaction of an aromatic alcohol with an aldehyde (usually phenol with formaldehyde).

Pitch: Residual petroleum product used as a precursor in the manufacture of certain carbon fibers.

Plied yarn: Two or more yarns collected together with or without twist.

Ply: Constituent single layer used in fabricating or occurring within a composite structure. Also, the number of single yarns twisted together to form a plied yarn.

Ply orientation: Acute angle (theta) - including 90° - between a reference direction and the ply principal axis. The ply orientation is positive if measured counterclockwise from the reference direction and negative if measured clockwise.

Polyacrylonitrile (PAN): Base material in the manufacture of some carbon fibers.

Polyimide: Highly heat-resistant polymer resin.

Polymer: Large organic molecule formed by combining many smaller molecules (monomers) in a regular pattern.

Polymerization: Chemical reaction that links monomers to form polymers.

Precursor: Material from which carbon fiber is made by pyrolysis. Common precursors are polyacrylonitrile (PAN), rayon and pitch.

Preform: Pre-shaped fibrous reinforcement, normally without matrix, but often containing a binder to facilitate manufacture; formed by distribution of fibers to the approximate contour and thickness of the finished part, typically on a mandrel or mock-up.

Prepreg: Admixture of fibrous reinforcement and polymeric matrix used to fabricate composite materials in a form that can be stored for later use. It may be sheet, tape, tow or fabric. For thermosetting matrices the resin is usually partially cured or otherwise brought to a controlled viscosity, called B-stage. Additives such as catalysts, inhibitors and flame-retardants can be added to obtain specific end-use properties and improve processing, storage and handling characteristics.

Pseudarthrosis: A false joint, formed around a displaced bone end after dislocation.

Pultrusion: Continuous process for manufacturing composites in rods, tubes and structural shapes having constant cross-sections. After the reinforcement is passed through the resin-impregnation bath, it is drawn through a shaping die to form the desired cross section; curing takes place before the laminate can depart from that cross section.

Q

Quasi-isotropic laminate: A laminate approximating isotropy by orientation of plies in several or more directions.

R

Rheumatoid arthritis: A form of arthritis that is second most common rheumatic disease. It typically involves the joints of the finer, wrists, feet, and ankles and often the hips and shoulders.

Reinforcement: Key element added to the matrix to provide the required properties (primarily strength); ranges from short fibers through complex textile forms.

Resin: Solid polymeric material, often of high molecular weight, which exhibits a tendency to flow when subjected to stress, usually has a softening or melting range, and usually fractures conchoidally. As composite matrices, resins bind together reinforcement fibers.

Resin-rich: Filled with excess resin and thus departing from a consistent resin/fiber ratio.

Resin transfer molding (RTM): Molding process in which catalyzed resin is transferred into an enclosed mold into which a fibrous reinforcement has been placed. The mold and/or resin may or may not be heated. RTM combines relatively low tooling and equipment costs with the ability to consolidate large structural parts.

Resorption: Loss of substance through physiological or pathological means.

Roving: Large filament-count tow.

S

S-glass: Denotes "structural glass" a magnesia/ alumina/silicate glass reinforcement designed to provide very high tensile strength. Used in high-performance composites.

Sealant: Paste or liquid applied to a joint that hardens in place to form a seal.

Shear: Action or stress resulting from applied forces that causes or tends to cause two contiguous parts of a body to slide relative to each other.

Silicon carbide fiber: Reinforcing fiber with high strength and modulus; density is equal to that of aluminum. May be formed as wires by chemical vapor deposition onto a carbon-filament core, or as filaments. Used in both organic and metal-matrix composites.

Specific gravity: Density (mass per unit volume) of a material divided by that of water at a standard temperature.

Stacking sequence: Arrangement of ply orientations and material components in a laminate specified with respect to some reference direction.

Stiffness: Measure of the resistance of a material to deformation. The ratio of applied stress to resulting strain for a particular material.

Strain: Deformation resulting from applied stress. Measured as the change in length per unit of length in a given direction, and expressed in percentage or as inches per inch.

Stress: Internal resistance to change in size or shape, expressed in units of force (load) per unit area.

Stress crack: External or internal cracks in a composite caused by tensile stresses; cracking may be present internally, externally or in combination.

Symmetric laminate: Laminate in which the stacking sequence for the plies located on one side of the geometric midplane are the mirror image of the stacking sequence on the other side of the midplane.

T

Tape: Thin unidirectional prepreg in widths up to 12 inches for carbon fiber.

Tensile strength: Maximum tensile stress sustained by a specimen before it fails in a tension test.

Thermal conductivity: Ability to conduct heat.

Thermoplastic: Class of plastics that can be repeatedly softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and that in the softened state can be shaped by flow into articles by molding or extrusion.

Thermoset: Class of plastics that, when cured using heat, chemical or other means, changes into a substantially infusible and insoluble material. Once cured, a thermoset cannot be returned to the uncured state.

Toughness: Measure of the ability of a material to absorb energy.

U

Unidirectional (UD): Referring to fibers that are oriented in the same direction, such as unidirectional fabric, tape or laminate.

V

Vacuum-bag molding: Molding technique wherein the part is cured inside a layer of film from which entrapped air is removed by vacuum.

Varus: Describing any deformity that displaces the hand or foot towards the midline.

Viscosity: Tendency of a material to resist flow. Viscosity is measured in comparison with water. The higher the number, the less flow.

Void: Any pockets of enclosed gas or air within a composite.

Volatiles: Materials, such as water and alcohol, in a sizing or resin formulation that can be vaporized at room or slightly elevated temperatures.

W

Water absorption - Ratio of weight of water absorbed by a material to the weight of dry material.

Wetout: Saturation with resin of all voids between strands and filaments.

Woven roving: Heavy, coarse fabric produced by weaving continuous roving bundles.

X

X-axis - Usually, the axis in the plane of the laminate used as 0° reference. Typically, the y-axis is the axis in the plane of the laminate perpendicular to the x-axis, and the z-axis is the reference axis normal to the laminate plane in the composite laminate. (See also laminate coordinate axes, off-axis laminate and principal axis.)

Y

Yarn: Continuous, ordered assembly of essentially parallel, collimated filaments, usually with a twist.

Young's modulus: Ratio of normal stress to the corresponding strain for tensile or compressive stresses less than the proportional limit of the material.

كل عام، مما يجعل التدخل الجراحي في هذه الحالات ضروريا جدا. تم استخدام نوعين من الألياف التي تدخل في تصنيع هذه البدائل، النوع الأول هو الألياف الزجاجية(Glass fibers)، أما النوع الثاني فهو عبارة عن مادة هجينة تتكون من ألياف الكربون و الأراميد (Aramid/Carbon fibers) مدعومة باستخدام راتنج الفينيل ايستر. كما تم استخدام نوعين من طرق التصنيع هما:

(١) الكبس الحراري (Hot Press)

(٢) التسريب بالتفريغ (Vacuum Infusion)

و بعد ذلك تم تقسيم العينات إلى ثلاث مجموعات ، كل مجموعة تحتوي على ثمان عينات، و لأغراض هذه الدراسة تم تعريض بعض هذه العينات إلى ظروف بيئية حمضية تمثل نفس الخصائص البيئية الموجودة داخل جسم الانسان، بينما تم استخدام العينات الأخرى كما هي دون تعريضها إلى الظروف البيئية الحمضية.

شملت عملية التقييم الأمور التالية:

(١) الاختبارات الميكانيكية

(٢) حسابات الزيادة في وزن العينات

(٣) دراسة العينات باستخدام المجهر الماسح الالكتروني

جاءت نتائج الدراسة كما هي متوقعة، حيث أن تأثير الرطوبة على أداء هذه المواد أدى إلى تخفيض متانة و صلبية المواد المركبة باستخدام طريقة التسريب بالتفريغ، بينما تم الحصول على نتائج غير متوقعة لأداء هذه المواد المركبة باستخدام طريقة الكبس الحراري، حيث وجد أن صلبية و متانة المواد المركبة قد ارتفعت بدلاً من من أن تنخفض بعد تعرضها للرطوبة، و السبب في ذلك يرجع إلى نقص كمية الراتنج فينيل ايستر الموجود بين السطوح الفاصلة بين الألياف و الراتنج.

الخلاصة

يعتبر استخدام المواد الأحيائية (Biomaterials) في جراحة تقويم المفاصل من العمليات الناجحة في المجالات الطبية الحديثة ، و تعتبر جراحة تقويم مفصل الحوض (Total Hip Joint Replacement) من أشهر و أنجح العمليات الجراحية، و من المواد الطبية التي كانت و لا تزال تدخل في تصميم و اختراع بديل مفصل الحوض هي المواد المعدنية (Metals). و لكن اكتشف أن استخدام هذه المواد المعدنية في تصميم بديل مفصل الحوض له جوانب سلبية كثيرة. السلبية الأولى هي أن صلبية هذه المواد المعدنية (Stiffness) مرتفعة بالمقارنة مع صلبية العظام. فمثلاً معامل المرونة لمادة التايتينيوم حوالي 110 جيجا باسكال و معامل المرونة لمادة سبيكة الكوبلت و الكروميوم حوالي 210 جيجا باسكال، بينما يتراوح معامل المرونة للعظام من 15 إلى 25 جيجا باسكال. إن عدم التوافق بين صلبية المواد المعدنية المستخدمة و صلبية العظام يؤدي إلى انحلال العظام و بالتالي يؤدي الى انفكاك و كسر المفصل. المشكلة الثانية هي أن هذه المواد المعدنية تطلق أيونات ضارة بالجسم مما يسبب حساسية مفرطة للمريض.

من أجل التغلب على مشاكل الصلبية و المشاكل الأخرى المتعلقة باستخدام هذه المواد المعدنية، توصلت التكنولوجيا الى اكتشاف مواد جديدة تسمى بالمواد المركبة (Composite Materials) كبديل للمواد المعدنية. إن استخدام المواد المركبة في عمليات جراحة تقويم المفاصل كان له الأثر و الفائدة الكبيرة. فمن هذه المميزات و الفوائد نذكر على سبيل المثال: الخصائص الميكانيكية الفائقة مثل شفافية هذه المواد للأشعة و خفة الوزن و التوافقية الأحيائية. و تعرف هذه المواد أيضاً على أنها منخفضة الصلبية مما يجعلها تتوافق مع صلبية العظام. و من خصائص هذه المواد أيضاً أنه يمكن التحكم بخصائص المتانة (Strength) و الصلبية (Stiffness) و جعلها قريبة من خصائص العظام. فمثلاً تتراوح متانة هذه المواد من 70 إلى 1900 ميجا باسكال، و يتراوح معامل الصلبية من 1 إلى 170 ميجا باسكال. إن خاصية التحكم في معاملات المتانة و الصلبية يجعل العظم مستقراً في مكانه و قريبا من المعدلات الفيزيولوجية الطبيعية. و بالتالي سيؤدي استخدام هذه المواد إلى التخلص من مشاكل انفكاك و كسر بديل المفصل.

إن الهدف الأساسي من هذه الدراسة هو اختيار المواد المركبة لبديل مفصل الحوض و المصنوع من مواد هجينة. من أجل الوقوف على خلفية هذا الموضوع، تم اجراء احصائية ميدانية لحالات عمليات تبديل مفاصل الحوض في مستشفيات الدولة، و تبين من خلال هذه الاحصائية أن عدد حالات عمليات تبديل مفاصل الحوض في تزايد مستمر

جامعة الامارات العربية المتحدة

عمادة الدراسات العليا

برنامج علوم و هندسة المواد

اختيار المواد لبديل مفصل الحوض الصناعي المصنوع من المواد المركبة

إعداد

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ضمن متطلبات الحصول على درجة الماجستير

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