Biomaterials Course Development for Undergraduate Engineering Education

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Abstract

The use of biomaterials has been continuously rising in the globe because of the developments in medical fields. Without these materials, quality of the life will most likely be lower and lifetime expectance will probably be shorter. In order to increase academic and public attention to biomaterials, we have developed a three credit hours biomaterials course "Biomaterials" in the Department of Mechanical Engineering at Wichita State University (WSU), and taught in Fall 2008. The lectures focus on basic biomaterials, characterization, biocompatibility, biodegradability, toxicity, as well as potential commercial applications. During the lectures, the engineering students are expected to gain an understanding of biomaterials concepts and their properties.

Keywords: Biomaterials, medical applications, course development and future directions.
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1. INTRODUCTION

Biomaterials are special materials that have been used for over 50 years in several medical applications. The major applications include joint replacements, blood vessel prostheses, bone plates, bone cement, heart valves, artificial ligaments and tendons, dental implants, skin repair devices, contact lenses and cochlear replacements [1-5]. The main issue in the applications of biomaterials is that they must be biocompatible with the body and mechanically durable, all of which must be proofed before placing into the body. These biomaterials are usually subjected to the same requirements with the new drugs put in the market [2]. In the present course, our engineering students learn all the subjects specified here in detail.

Biomaterials can be in the forms of metals and alloys, ceramics, polymers and composites. Figure 1 shows the several biomaterials utilized for a variety of medical purposes [1]. **Metals and alloys** are used as biomaterials due to their excellent mechanical, surface and thermal properties. Some of the metals and alloys include 316L stainless steel, Ti based alloys, Cr based alloys, Ni based alloys, Au, Ag and Pt based metals and alloys, and amalgams (Hg, Ag and Sn). The properties of metallic materials are related to the grain size and shape, surface roughness and imperfections in the crystal structure [1]. However, some studies showed that the surface of metals can be active and interact with the tissue or organs and produce toxic corrosion products. This limits the use of metallic materials in various applications [3,4].

Ceramic biomaterials (bioceramics) are highly biocompatible materials and possess several superior properties: (***i***) they can have structural functions as joint or tissue replacements, (***ii***) can be used as coatings to improve the biocompatibility of the implants, (***iii***) can allow growing cells and tissues on them, and (***iv***) can be used to replace some of the entire body parts. The better chemical and thermal stability, strength, wear resistance and durability make ceramics good candidate materials for surgical implants. The main disadvantages of the ceramics are that they are highly brittle, have low tensile strength, can mechanically fail during the use and are not reparable when broken. Some of the ceramic biomaterials include hydroxyapatite, alumina, zirconia, calcium phosphate, insoluble glasses, bioactive glasses, porcelain and carbons [1]. Bioceramics have higher porosity in their structure (Figure 2), which is a critical parameter for growth and integration of cells and tissues.

Figure 1: The several biomaterials utilized for various biomedical applications.

Polymeric biomaterials possess a wide spectrum of physical, chemical, physicochemical and biological properties that allow them to be used in a wide verity of medical applications. They can be both biocompatible and biodegradable depending on the chemical structures and applications. Some of the biocompatible polymers include (but are not limited to) ultra-high molecular weight polyethylene, polymethyl-methacrylate, poly(etheretherketone), polytetrafluoroethylene, polyethleneterephthalate, polyvinyl chloride, polyethylene, polypropylene, etc. Biodegradable polymers include polylactide (PLA), polyglycolide (PGA), polycaprolactone (PCL), and their copolymers. It is reported that the degradation of the materials yields the corresponding hydroxy acids, making them safe for *in vivo* use [1]. Ductility, low tensile and compression strengths, and high wear rate result in a high generation of wear debris, which reduce the applications of some of the polymeric biomaterials [2,3].

Composite biomaterials are new classes of materials formed by a biocompatible matrix (resin) and a reinforcement of synthetic materials (e.g., carbon and glass fibers). There are also natural composite biomaterials including bone, wood, dentin, cartilage, turtle shell, chicken feather, and skin. These materials are used for drug, gene and DNA delivery, tissue engineering, joint and bone replacement, cosmetic, orthodontics (dental), etc. These materials usually imitate the structures of the living parts of the body. Figure 3 also shows the schematic views of biomaterials used in the human body [1].

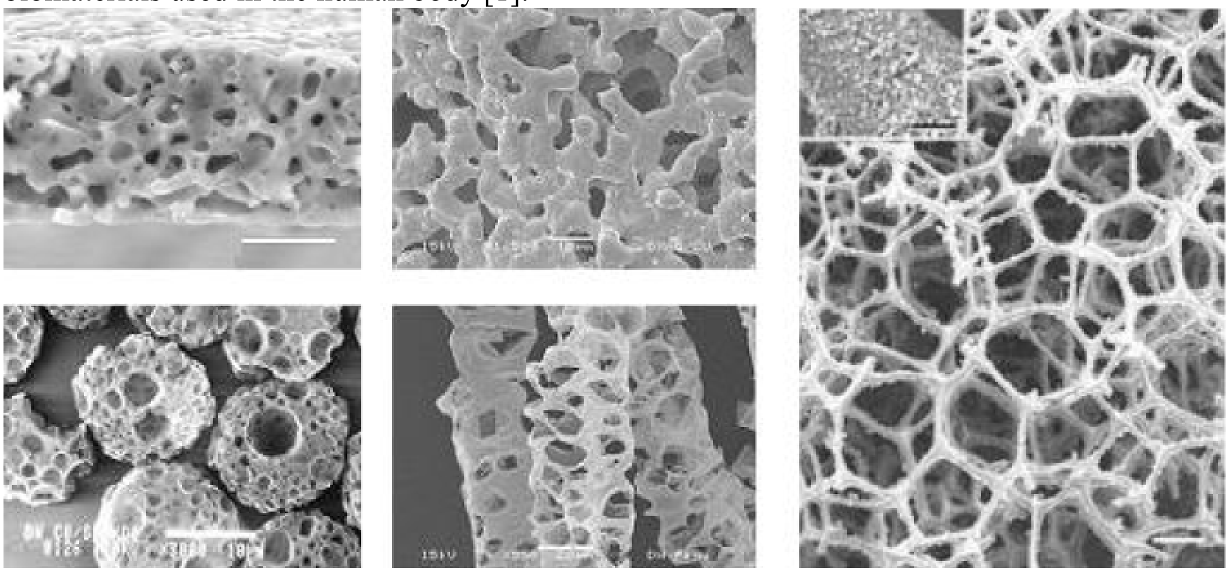

Figure 2: Various micro structures of ceramic biomaterials for cell and tissue growth.

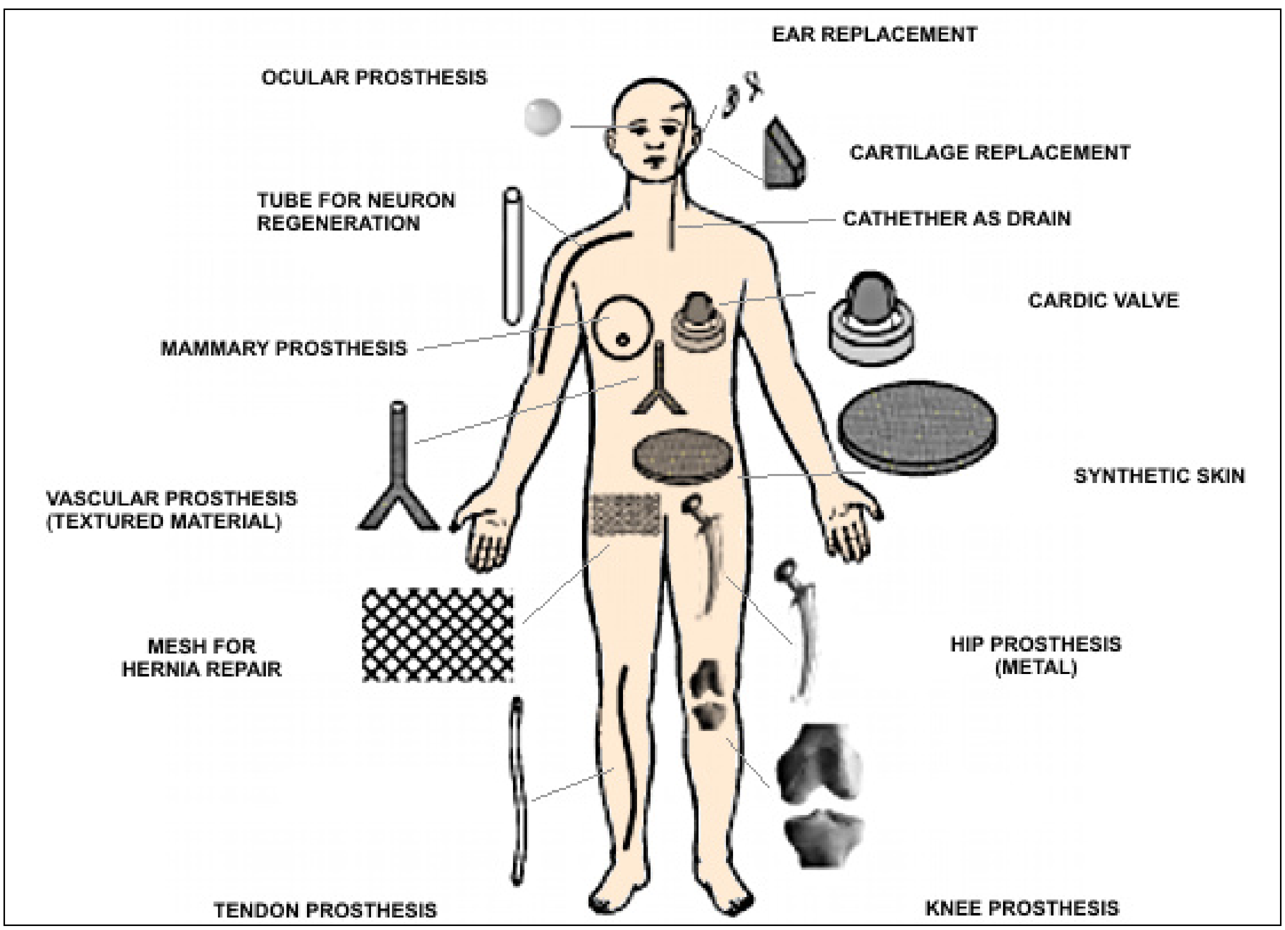

Figure 3: The schematic views of various biomaterials used in the human body.

2. SUBJECTS OF BIOMATERIALS SCIENCE

There are a number of important subjects in biomaterials science and engineering that students learn in the present course. Some of those subjects are given below [1-5]:

Toxicology: Unless otherwise specified, toxicology is a study of adverse effects of biomaterials on the living cells and organs of the body. It usually deals with symptoms, mechanisms, treatment and detection. However, there are some biomaterials or drugs specifically designed to be toxic to target deadly diseases (e.g., cancer tumors) and destroy them [2,12].

Biocompatibility: Biocompatibility is mostly related to the behavior of biomaterials in the body conditions. It is difficult to measure directly, so generally defined in terms of success for specific applications, such as implants and drug delivery systems [1].

Biodegradability: It is simply a phenomenon that natural and synthetic biomaterials are capable of decomposing in the body conditions without leaving any harmful substances behind. Sometimes, it leaves behind useful nutrients, which may be useful for disease treatment and body recovery [3].

Targeted Drug Delivery: Drug targeting is achieved through venous injection of drug-loaded materials, which freely circulate throughout the body. Under the external forces or effects (e.g., magnetic, ultrasound, electric, temperature, light, X-Rey, pH and mechanical), these materials are trapped and concentrated at the local site, and then start releasing the drug molecules. Three main mechanisms for releasing drug molecules from the materials into a blood vessel or tissue are diffusion, degradation, and swelling followed by diffusion [6-10].

Healing: One of the main considerations of biomaterials is that when they are placed in the body, they should heal the disfunctioning part of the body.

Mechanical Durability: The best materials for medical applications are not only biocompatible, but also have better physical properties similar to those of the bones, tissues or other biological systems to be replaced or repaired. Biomaterials must perform to certain standards, and also cope with tensile and compression stresses. Some of the comparative properties of natural and synthetic biomaterials are given in Table 1. As is seen, every material has its own special Young's modulus, density and compression and tension strength, which in turn determine their specific applications in different biomedical purposes [1-4]. Thus, it is essential that all biomaterials are well designed and are tested before the medical applications.

Biomaterials Corrosion: Body fluid has all kinds of anions (Cl^-, $HPO42^-$ and $HCO3^-$), cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}), organic substances (proteins and enzymes), plasma, water and dissolved oxygen along with body temperature (37°C). Thus, body has all possible environments for metallic biomaterials corrosion [1]. Figure 4 shows the corrosion formation on a hip joint at the junction between the modular head and neck of prosthesis.

Failure of Biomaterials: Although several biomaterials meet the requirements of biocompatibility for medical use, unfortunately, some of the biomaterials do not possess sufficient mechanical durability in a large number of cases. Thus, revision surgeries are necessary in approximately 7% of hip and 10% of knee replacements after 10 years of use. Biomaterials can fail through several ways: (***i***) insufficient mechanical durability, higher fatigue, damage accumulation, and wear, and (***ii***) provoking adverse biological responses, such as failure arises by bone loss or bone death due to the inappropriate stressing of the peri-prosthetic tissues, failure of bone ingrowth due to the relative motion between implant and tissues or osteolysis due to the wear particles [11]. Figure 4 also shows the degraded polymeric knee joint after a long period of use [1].

Table 1: The comparative mechanical properties of biomaterials.

Material	Young's Modulus E (GPa)	Density ρ (g/cm³)	Strength (MPa)
Hard tissue	17	1.8	130 (tension)
Tooth, bone, human compact bone, longitudinal direction			
Tooth dentin	18	2.1	138 (compression)
Tooth enamel	50	2.9	
Polymers			
Polyethylene (UHMW)	1	0.94	30 (tension)
Polymethyl methacrylate, PMMA	3	1.1	65 (tension)
PMMA bone cement	2	1.18	30 (tension)
Metals			
316L Stainless steel (wrought)	200	7.9	1000 (tension)
Co–Cr–Mo (cast)	230	8.3	660 (tension)
Co–Ni–Cr–Mo (wrought)	230	9.2	1800 (tension)
Ti6A14V	110	4.5	900 (tension)
Composites			
Graphite-epoxy (unidirectional fibrous, high modulus)	215	1.63	1240 (tension)
Graphite-epoxy (quasi-isotropic fibrous)	46	1.55	579 (tension)
Dental composite resins (particulate)	10–16		170–260 (compression)
Foams			
Polymer foams	10^{-4}–1	0.002–0.8	0.01–1 (tension)

3. COURSE CONTENTS

3.1 Course Learning Objectives

This course, "Biomaterials", is a three credit hour course at 600 level, and meets twice a week for 75 minutes each meeting time during the 14-week semester. This serves as an elective for the students in the Department of Mechanical Engineering and other College of Engineering's senior and graduate level students at WSU. The learning objectives of the proposed course offered in Fall 2008 can be described. After the completion of the course, all the registered students were able to:

- Understand the fundamental principles of biomaterials and their properties,
- Apply modern analytical techniques for characterization of biomaterials,
- Apply computational techniques to biomaterials,
- Understand the surface area and toxicity,
- Understand the processes and cost analysis, and
- Demonstrate effective communication and teamwork skills through technical presentations and reports in term projects.

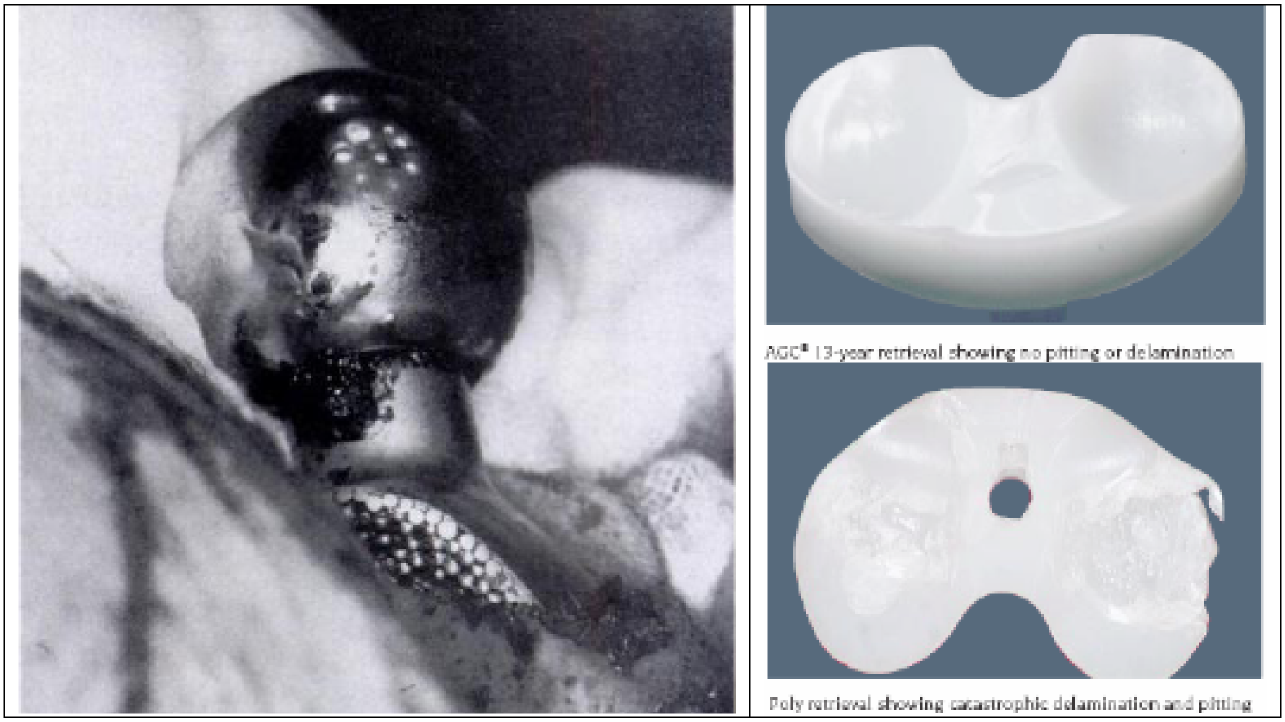

Figure 4: Metallic corrosion on a hip joint (left) and degraded polymeric knee joint (below).

3.2 Course Textbook

Two books are required for the present course, which are given below. In addition to these books, we also prepared and posted our own PowerPoint lecture notes on blackboard using information in the books and other sources.

1. Wong, J.Y. and Bronzino, J.D. "Biomaterials," CRC Press, 2007
2. Sih, D. "Introduction to Biomaterials," World Scientific, 2006.

A number of homework assignments and a term project regarding the biomaterials subjects were given to students to help satisfy their scientific interests in biomaterials. It is believed that this class broadened the horizons of both undergraduate and graduate students and promoted their interests into research activities of biomaterials. The prerequisite of this course is Materials Engineering (ME 250). The units of the assessment are given below:

- Homework :20%
- Term Project :20%
- Exam I :30%
- Exam II :30%

3.3 Course Outline

The present course mainly deals with biomaterials, properties, biomedical applications, biocompatibility and biodegradability, toxicity of the materials, etc. Table 2 shows the course outline in detail.

Table 2: The outline of "Biomaterials" course taught for engineering students in Fall 2008.

Time Period	Lecture Topics
Week 1a	Course introduction
Week 1b	Importance of biomaterials
Week 2a	Metallic biomaterials - I
Week 2b	Metallic biomaterials - II
Week 3a	Ceramics biomaterials - I
Week 3b	Ceramics biomaterials - II
Week 4a	Polymeric biomaterials - I
Week 4b	Polymeric biomaterials - II
Week 5a	Composite biomaterials - I
Week 5b	Composite biomaterials - II
Week 6a	Biodegradable materials
Week 6b	Biocompatible materials
Week 7a	Soft tissue replacement
Week 7b	Hard tissue replacement
Week 8a	Tissue engineering
Week 8b	Dental implants
Week 9a	Biosensors
Week 9b	Biodevices
Week 10a	Targeted drug delivery
Week 10b	Biomaterials corrosion and degradation
Week 11a	Term project presentation
Week 11b	Term project presentation
Week 12a	Term project presentation
Week 12b	Term project presentation

4. COURSE ASSESSMENT SURVEY QUESTIONS

After the course was taught with over 50 under graduate and graduate students, a list of survey questions was given to the students to scale from 1 (lowest) to 10 (highest). Following are the questions for quantitative assessment, which are usually asked in the Accreditation Board for Engineering and Technology (ABET). The survey results are given in Table 3. As can be seen from the survey results, most of the engineering students who took the survey scaled between 6 and 10, which confirms that newly developed biomaterials course is well understood and established.

1) Please rate your level of understanding of the fundamental concepts in biomaterials,
2) Please rate your ability to apply the fundamental principles of biomaterials,
3) Please rate your ability to apply modern analytical techniques to biomaterials,
4) Please rate your ability to apply computational techniques to biomaterials,
5) How do you rate your ability to effectively communicate technical information in writing?
6) How do you rate your teamwork skills?
7) How do you rate your ability to make technical presentations?
8) How do you rate your ability to be a self-grower with regard to life long learning?

Table 3: Results of student survey regarding the biomaterials course.

Questions	Number of students scaled from 1 to 10									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
#1	0	0	0	0	0	2	1	4	5	6
#2	0	0	0	0	1	1	2	4	3	7
#3	0	0	1	0	2	1	2	3	5	6
#4	0	0	0	0	1	2	3	3	4	5
#5	0	1	0	1	0	1	3	5	4	6
#6	0	0	0	0	0	0	1	4	5	6
#7	0	0	0	1	0	1	2	3	4	5
#8	0	0	0	0	1	1	1	3	4	5

Additionally, SII questions were asked, in which the students would list their personal strengths, improvement areas and insights about their knowledge of biomaterials. The following questions were chosen for an additional post course assessment to facilitate continuous improvement on biomaterials and related topics:

1) What are the three strengths of this course?
2) What are the top three things that you have learned?
3) What are the three improvements for this course that would help you learn better?
4) How can these improvements be made?
5) What action plans can be put in place to help you learn more?
6) What have you learned about your own learning process?
7) Is there anything else you would like the instructor to know about the class?

Several different answers were received from the students depending on the background, field of interest, level of students (BS and MS) and employment. The common answers for the question number 1 are "group discussion, videos, animations, colorful pictures and drawings describing the subjects". The other common answers for the question number 2 are "biomaterials are special materials for human life". The answers to other questions varied. The SII questions proof that the students pay more attention to the visual and active learning in the class, and gain very useful information about the biomaterials.

5. CONCLUSION

A biomaterials course "Biomaterials" has been developed in the Department of Mechanical Engineering at WSU and taught in Fall 2008. This course was a three credit hour course and met twice a week for 75 minutes during the 14-week semester. We covered pretty much all biomaterials related subjects that students may need in their future careers. Homework sets and a term project were given students to apply knowledge learned in the course for creative biomaterials selections and applications. The survey results confirmed that this course improved the fundamental and practical knowledge of the students on biomaterials and close related subjects.

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