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Enhancement of surface properties of biomaterials using plasma-based technologies

Paul K. Chu *

Department of Physics & Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong

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Abstract

Development of new biomaterials typically takes a long time due to extensive tests and lengthy approval procedures. Plasma surface modification offers an exciting alternative by modifying selective surface mechanical and biological properties of conventional biomaterials to suit particular needs. Hence, materials that possess favorable bulk properties can have their surfaces redesigned to cater to biomedical applications. Plasma surface modification is a popular method to improve the multi-functionality, tribological and mechanical properties, as well as biocompatibility of artificial biomaterials and medical devices. Here, our recent research work on plasma modification of orthopedic nickel-titanium shape memory alloys and cardiovascular materials, namely diamond-like carbon is described. The shape memory effect and super-elasticity of NiTi alloys allow for a novel surgical technique for gradual correction of spinal deformity. However, out-diffusion of toxic Ni ions into human tissues is a health concern and plasma treatment is an excellent method to impede Ni leaching while the super-elastic properties of the bulk alloy can be retained. The two important requirements for cardiovascular materials such as those used in artificial heart valves, are that they must possess adequate surface mechanical properties and blood compatibility. Our recent experiments indicate that doping diamond-like carbon with elements such as nitrogen and phosphorus can enhance the biocompatibility of the materials.

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Keywords: Plasma processing; Biomaterials; Nickel-titanium shape memory alloys; Diamond-like carbon

1. Introduction

Bio-integration of artificial biomaterials requires that the reactions occurring at the interface between the biomaterial surface and host tissues do not induce deleterious effects such as inflammation and irregular tissue response. Unfortunately, materials that possess favorable bulk properties such as strength frequently have inadequate surface biological properties such as blood compatibility. In this respect, surface modification plays an important role by providing a means to tailor selective surface properties without affecting the desirable bulk attributes of the materials [1]. Fig. 1 shows some of the common surface modification techniques. In particular, a number of plasma-based techniques are suitable for this purpose. They include radio-frequency (RF) glow discharge, electron cyclotron resonance (ECR) discharge, corona discharge, atmospheric plasma processes, sputtering, physical vapor deposition, chemical vapor deposition, plasma-assisted deposition, plasma implantation, plasma polymerization and grafting for polymeric surfaces, and plasma spraying [2]. Each technique has unique advantages and applications and the choice of the technique frequently depends on the reliability, reproducibility, and product yields [3], and plasma surface modification has become a hot research topic in biomaterials [4–6].

Among the various plasma treatment techniques, plasma immersion ion implantation and deposition (PIII&D) that was first introduced in the 1980s to circumvent the line-of-sight restriction of conventional beam-line ion implantation [7] offers advantages such as high efficiency, large area and batch processing, as well as small instrument footprint [8,9]. It has recently been applied to a variety of biomaterials research and development activities, such as orthopedic braces and materials [10–12], amorphous carbon films [13,14], hard tissue replacements [15,16], polymers [17–19], and titanium oxide [20]. In this paper, the recent developments in our laboratory pertaining to orthopedic

* Tel.: +852 27887724; fax: +852 27889549, +852 27887830.
E-mail address: paul.chu@cityu.edu.hk.

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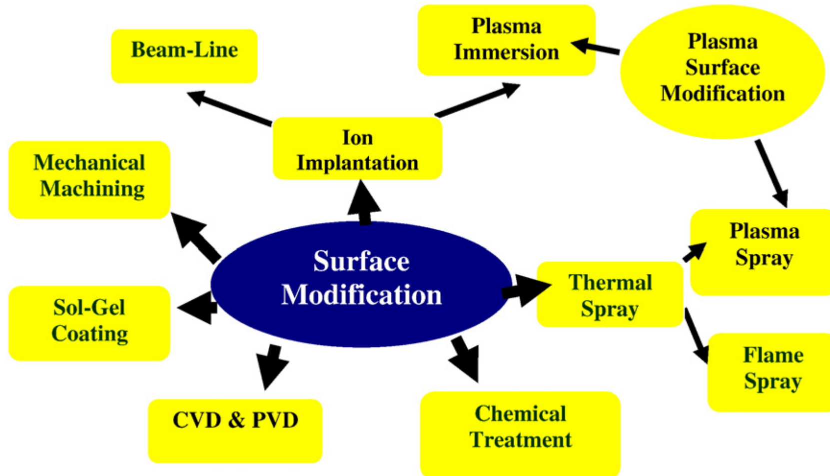

Fig. 1. Common surface modification techniques for biomaterials.

nickel-titanium shape memory alloys and doped diamond-like carbon are described.

2. Plasma treatment of orthopedic nickel-titanium shape memory alloys

Stainless steels and titanium alloys are currently the most widely used metallic orthopedic materials. Stainless steels are the oldest and remain one of the most preferred materials for internal fixation devices because of their favorable mechanical properties, cost effectiveness and acceptable bio-compatibility [21]. Commercial titanium and titanium alloys are the best choice for dental and cementless orthopedic implants because they possess superior bio-compatibility and corrosion resistance as well as low modulus [22]. A new class of materials, nickel-titanium (NiTi) alloys, has recently attracted attention as orthopedic materials due to their unique super-elastic and shape memory effects [23–25]. While some studies have suggested that NiTi is compatible with living tissues [26,27], adverse effects have also been reported. For instance, it has been found that the osteogenesis process and osteonectin synthesis activity in NiTi alloys are unfavorable compared to stainless steels and titanium alloys [28]. Another study has reported severe cell death rate on NiTi alloys and the problem is believed to stem from the poor corrosion resistance and toxic substances released from the substrate [29]. The supernatant and corrosive products from the NiTi substrate may result in the death of smooth muscle cells, especially when the concentration of the leached nickel exceeds 9 ppm [30]. Other studies have shown that nickel leached from the alloys causes detrimental effects to humans, especially for nickel hyper-sensitive patients, resulting in strong allergic reactions [31,32]. Hence, the corrosion resistance of the materials must be enhanced before the materials can be more widely used clinically. Some researchers have implanted tantalum and oxygen using plasma techniques to improve the surface properties of NiTi alloys [33,34]. Our group has been

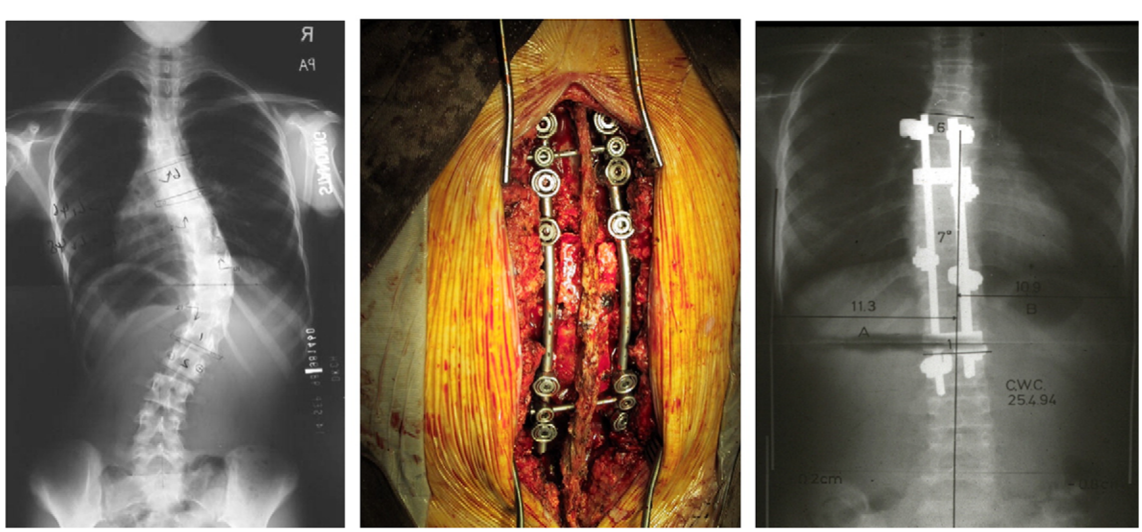

Fig. 2. Conventional surgical technique for correction of severe spinal deformity: (Left) X-ray of spine of a patient with scoliosis; (Middle) Surgeon straightening the spine with stainless steel rods; (Right) X-ray of spine after surgery.