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Chapter 10

NiTi Shape Memory Alloys, Promising Materials in Orthopedic Applications

Marjan Bahraminasab and Barkawi Bin Sahari

Additional information is available at the end of the chapter

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1. Introduction

A large number of materials are continuously being developed to meet the requirements for different engineering applications including biomedical area. However, development of a material in this field is a challenging issue especially for those devices that are implanted in the human body, because the material must fulfill an array of fundamental biological and mechanical requirements. Among these, orthopedic applications require careful attention as a result of ageing population worldwide, large number of injuries and the demand for higher quality of life. A wide range of materials including metals, alloys, ceramics, polymers and composites are currently used in this area, but unfortunately, some have shown tendencies to cause device failure after long term use in the body since they cannot fulfill some vital requirements (Geetha, Singh et al. 2008; Bahraminasab, Hassan et al. 2010). Developing or applying an optimal material, therefore, can cause the implant to last longer and to avoid the huge cost related to the inappropriate or unsuitable choice of materials. Shape memory alloys (SMA) have provided new insights into biomedical area for cardiovascular, orthopedic and dental applications, and for making advanced surgical instruments. The biomedical success of these materials is due to their unusual properties, which makes them superior to conventional materials. Among many SMAs, NiTi alloy is considered to be the best because of its superb characteristics. NiTi alloy possesses most of the necessities for orthopedic implantation and is used in a large number of applications. Therefore, it is worth to highlight the orthopedic applications of this material. The reminder of this chapter is organized as follows; section 2 discusses on biocompatibility of NiTi shape memory alloy in both bulk and porous forms, followed by a brief review of some current NiTi applications in section 3. After that section 4 introduces one of the potential applications of this material in orthopedics, which is the femoral component of knee prosthesis. The chapter ends with discussion and conclusion in in sections 5 and 6, respectively.

2. Biocompatibility of NiTi

Enthusiasm to apply NiTi in implants has been tempered by the concern related to its biocompatibility. Biocompatibility is related to the capability of material to exist in contact with human body tissues without causing an unacceptable degree of harm to the body. Furthermore, the materials should have the ability to interact with the biological environment to improve the biological response, the tissue-surface bonding, and to enhance the ability to undergo a progressive degradation when new tissues grow and heal. Of the two metal elements in NiTi alloys, titanium is well recognized to be biocompatible with superb long-term corrosion resistance. In contrast to Ti, Ni release from the surface of NiTi implants has been a concerning issue because the dissolution and concentration of Ni ions or wear debris above a certain amount causes some allergic reaction and biocompatibility problems including pneumonia, chronic sinusitis and rhinitis, nostril and lung cancer for patients (Mantovani 2000; Kapanen, Ryhanen et al. 2001; Machado and Savi 2003). However, most of in vivo studies of NiTi implantation and in vitro experiments exhibited good biocompatibility of this material (Castleman, Motzkin et al. 1976; Ryhaenen, Kallioinen et al. 1998; Kapanen, Ryhanen et al. 2001). The good corrosion resistance of this material can be attributed to its crystal structure stability, which impedes the separation and release of Ni ions. Therefore, it seems that the actual risk of large Ni leaching from wear and corrosion phenomena may potentially be overexaggerated (Es-Souni and Fischer-Brandies 2005). The titanium content of these alloys is readily oxidized and creates an outmost protective titanium oxide layer which act as a barrier to chemical attack and corrosion and confines the diffusion of Ni ions. This oxide layer, however, is not permanent and can be depleted by wear, corrosion, and fatigue. In this situation, NiTi repassivates and regenerate the oxide layer. The integrity of the protective titanium oxide layer is influenced by surface roughness, inhomogeneities, residues, porosity, and geometry. A certain toxicity usually observed in vitro studies, is most likely due to the higher amount of Ni concentrations in vitro that are not possible to achieve in vivo (Shabalovskaya 1996). The biocompatibility of NiTi alloys has been reported to be equal or better than that of titanium, Co–Cr alloys and stainless steels (Shabalovskaya 1996; Ryhanen 2000; Es-Souni and Fischer-Brandies 2005). Treatments such as surface oxidation, plasma immersion ion implantation (PIII), and laser surface modification reduce the amount of Ni leaching from the surface of NiTi implant to negligible amounts. For example, a treatment like dual electropolishing (EP) and photoelectrocatalytically oxidation (PEO) makes NiTi suitable for hard tissue replacements (Chu, Guo et al. 2009). A problem associated with this material, which seems to be important for orthopedic implants, is slow osteogenesis process and growth of a fibrous layer at interface of bone-implant (Berger-Gorbet, Broxup et al. 1996; Chen, Yang et al. 2004) generating weak anchorage between the implant and adjacent bone, and finally leading to micro-motion and loosening of the implant. Nevertheless, creation of a thin apatite layer on NiTi components in situ showed a large amount of new bone directly contacting with the host bone (Chen, Yang et al. 2004). In addition to this, since porous biomaterials for implants (either as porous coating or integral porous body) have attracted researchers' interest, it has been tried to produce porous NiTi alloys with different fabrication techniques such as self-

propagating high temperature synthesis process, capsule-free hot isostatic pressing and metal injection molding (Figure 1). The amount of porosity, pore size, microstructure and mechanical properties of the porous NiTi may depend upon the fabrication method. Porous NiTi has been reported to have good biocompatibility, comparable to the conventional porous stainless steel and titanium implant materials (Thierry, Merhi et al. 2002). However, the large exposed surface area directly interfacing the adjacent bone and tissue makes the issue of Ni release more serious than dense NiTi. Minimal Ni release can be obtained by surface engineering and treatments such as thermal annealing, oxygen plasma immersion ion implantation, hydroxyapatite (HAP) coatings, pre-soaking in simulated body fluid (SBF) solution, TiN and TiO_2-PVD coatings, and combinations thereof.

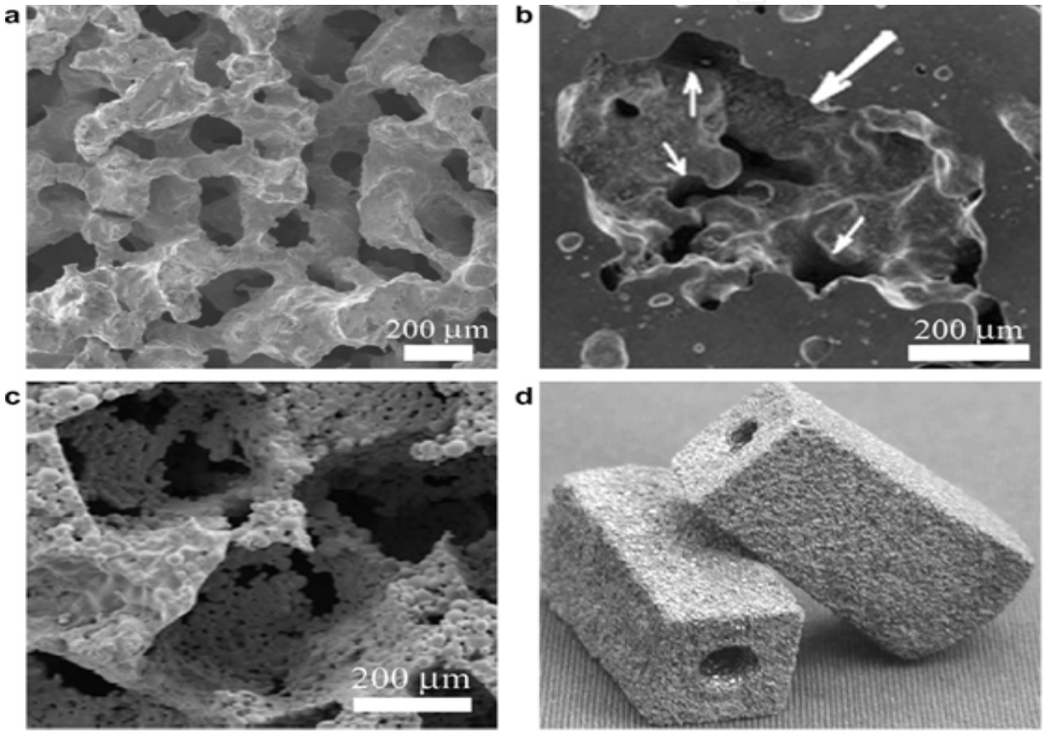


Figure 1. Scanning electron microscope Photographs of porous NiTi fabricated by three different techniques: (a) self-propagating high temperature synthesis process (about 65% porosity, 100–360 μm) (b) capsule-free hot isostatic pressing with argon expansion (42% porosity, 50–400 μm) (c) metal injection molding (70% porosity, 355–500 μm). (d) Image of commercial porous NiTi implant (Actipore™, Biorthex, Canada) for spinal fusion made by self-propagating high temperature synthesis process (Bansiddhi, Sargeant et al. 2008)

3. A brief review of NiTi SMAs in orthopedic applications

Shape memory alloys are a group of metallic materials with some unusual properties such as one-way and two-way shape memory effects, superelastic effect, high damping property and rubber-like effect. These characteristics make the material suitable for different orthopedic applications such as load-bearings, plates for bone fracture repair, internal fixators for long bone shafts, spinal correctors, vertebral spacers and bone distraction devices. Some of these applications are explained in the following subsections.

3.1. Spinal vertebral spacer

The spinal vertebral spacer is one of the applications of this material in orthopedics. The insertion of the spacer (disc) between two vertebrae provides the local reinforcement of the spinal column, avoiding any traumatic motion during the healing process. The employ of a shape memory spacer enables the use of a constant load regardless of the patient position with some degree of motion. This device is used to treat scoliosis. Figure 2 presents spinal vertebrae spacer in the in the original shape (right) and martensitic state (left).

Figure 2. Spinal vertebrae spacer (Duerig, Melton et al. 1990)

3.2. Spinal rod

Shape memory rod has been applied as a tool to help the scoliosis correction (Figure 3). NiTi is used in this application due to its ability to return to some predefined shape when subjected to a thermal treatment. It is expected that the spinal rod has the ability to keep the spine force loaded postoperatively, and it appears that this will take the advantage of spine viscous behavior to obtain extra correction. Furthermore, a postoperative fusion may prevent the long term failure of the system. The additional postoperative correction is expected to be obtained before the occurrence of this vertebral fusion.

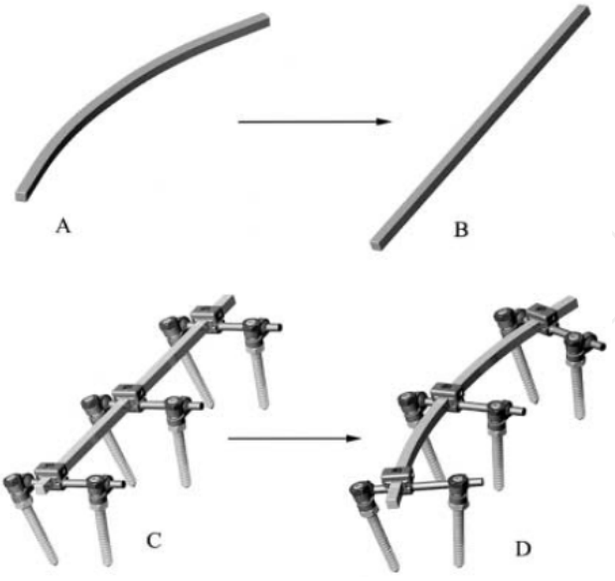


Figure 3. Spinal rod; (A) The original rod shape in the cold condition, (B) The straightened rod before insertion and heat treatment, (C) The implantation of straightened rod with anchorage system, (D) The recovered original curve of the rod with anchorage system after heat treatment (Wever, Elstrodt et al. 2002)

3.3. Medical staples

Another application of NiTi is related to the healing process of broken and fractured bones, using the shape memory effect. The shape memory orthopedic staples (Figure 4) are placed directly into the region of the break to compress the two parts of the bone. These staples, in their opened shape, are implanted to the fractured site of the bone, while through heating the staples tend to close, compressing the separated part of fracture. In this application, the heating is performed by an external device, and not due to the body temperature.

Figure 4. Medical staple before and after distraction (Laster, MacBean et al. 2001)

3.4. Plates for fractured bone

Shape memory plates also have been used to heal and recover the fractured bones, in the injured area where it is not possible to apply cast such as facial areas, nose, jaw, and eye socket. They are inserted to the fracture and fixed with intermediate screws (Figure 5). This maintains the original alignment of the bone and enables cellular regeneration. When these plates are heated, they tend to recover their previous shape (because of the shape memory effect) and exert a constant and uniform force on the two broken sections, which causes to join separated parts of fractures and helps in the healing process.

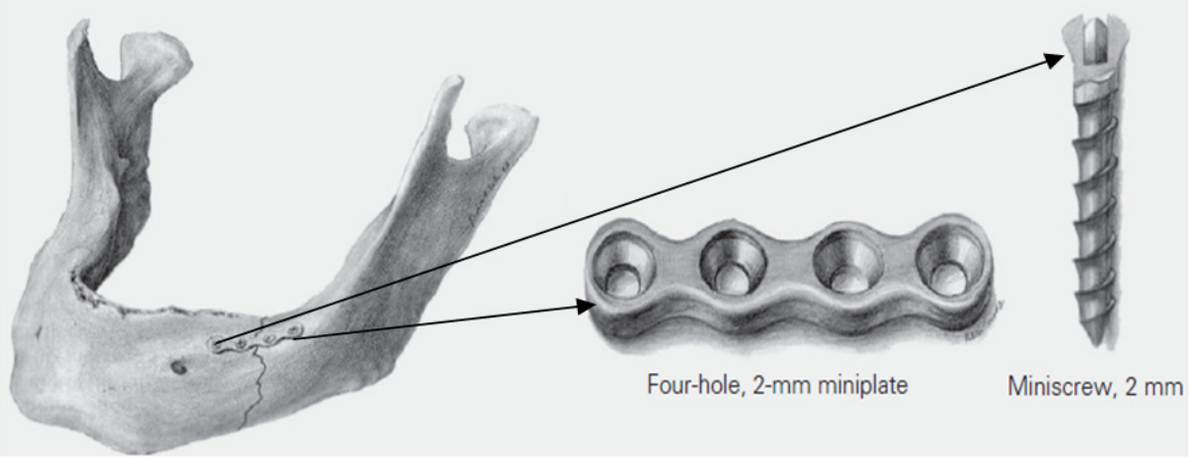


Figure 5. SMA plate for fractured human jaw bone and details of the plate and the screw (Machado and Savi 2003)

3.5. Nails for marrow cavity

These implants are applied where long bones, such as the femur, are broken. Treatment of this type of broken bones involves the hollowing out the bone marrow cavity of the two bone sections followed by the reconnection and introduction of a nail to enable the healing of the break. SMAs are used for nail material to apply controlled force to bone. The SMA nail can be manufactured to the desired shape for forced diaphyseal bone bending. Cooling down to the martensitic phase allows insertion of the shaped nail into the cavity, while at body temperature, the nail returns to its original shape, leading to a bending force.

3.6. Cruciate ligament

Considering the resistance to rupture and the maximum elastic deformation, the NiTi SMA can approach the behavior of a natural knee ligament. However, SMA could answer the demand for severe mechanical conditions imposed on the ligament prosthesis; the lack of fatigue resistance is a limiting factor for the prosthesis that is subjected to the repeated cyclic movements of the knee (Hagemeister, Yahia et al. 1995; Mantovani 2000). It should be pointed out that a new design of prosthetic ligament may lead to a solution for this weakness. NiTi alloy designed (in 1992) to reconstruct the anterior cruciate ligament in which the Nitinol strips were used with filaments, utilizing the unique property of Nitinol to change its shape by heating and cooling. The Nitinol alloy chosen for this application had an austenitic finish temperature of about 35°C, below the temperature of body. The contraction of the Nitinol wires, therefore, occurred (due to body temperature) on warming; caused the tibia and femur to be pulled together. On the other hand, Nitinol strips (used for anchorage to the tibia and femur) were also deflected by body heat after passing through the tibia and femur. The deflection of the strips, combined with the contraction of the wires, acted as a spring and counterbalanced the prosthesis loading during knee motion (Hedayat, Rechtien et al. 1992).

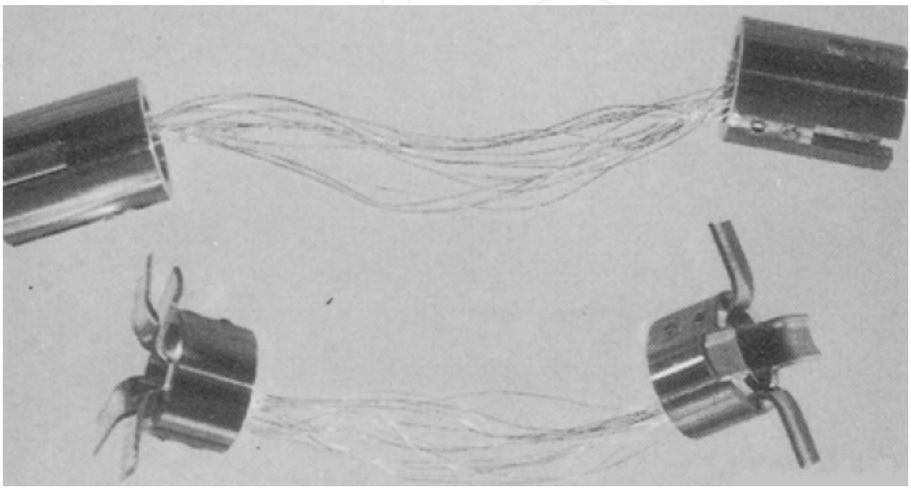
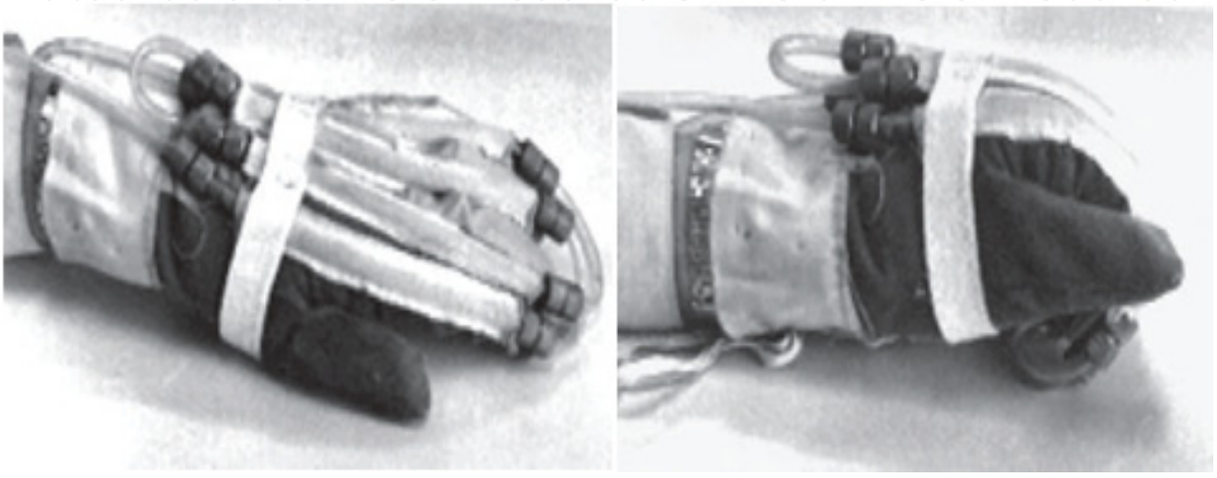


Figure 6. A carbon-coated NiTi prosthesis for reconstruction of the anterior cruciate ligament

3.7. Gloves in physiotherapy

NiTi SMAs are utilized in orthopedic treatment for physiotherapy of partially atrophied muscles. Physiotherapy gloves, which can reproduce the original movements of hands, were developed by locating the SMA wires on the region of fingers (Figure 7). These wires possess the two-way shape memory effect, so that heating the glove shortens the length of the wires and close the hand while cooling returns the wires back to their former shape and open the hand. In fact, the wires made of NiTi can withstand a large number of heating and cooling cycles, over time, without a decrease in performance (Gobert, Hoang et al. 2004).



(a) (b)

Figure 7. Gloves with SMA wires: (a) position at low temperature; (b) position at high temperature (Machado and Savi 2003)

4. Case study: Potential advantages of NiTi SMAs in knee implants

One of the most important current debates in orthopedic is the total joint replacements particularly hip and knee because of the simultaneous increasing number of both replacement and revision surgeries (Kurtz, Ong et al. 2007; Carr and Goswami 2009). One of the most serious concerns associated with revision surgery is the aseptic loosening of the components. Excessive wear between articular surfaces, stress shielding of the bone by prosthesis, and development of a soft tissue at the bone-implant interface are the main leading causes for aseptic loosening. Applying the best material for the implant components can reduce the wear debris, improve the load transfer system, and provide anchorage between the bone and the component interfacing the bone. Therefore, the optimal material can reduce the risk of prosthesis loosening.

4.1. Knee prosthesis components

Total knee replacement (TKR) typically has three main components: femoral component, tibial component (consisting of tibial tray and tibial insert), and the patellar component (Figure 8). The tibial insert and the patellar component are plastic parts such as ultra high

molecular weight polyethylene (UHMWPE) or cross-linked polyethylene (XLPE). The femoral component and the tibial tray are usually made of metals and alloys including titanium alloys, stainless steels or cobalt chromium alloys. Femoral component replaces the distal femur, hence; it interfaces the bone from the upper side and articulates against the polyethylene insert from the lower side. As a result, aseptic loosening of this component is involved with all the three main causes and it appears to be a more challenging issue. Therefore, there is a need to apply an optimal material for this component to reduce or avoid the loosening problem and provide longer lasting knee prosthesis.

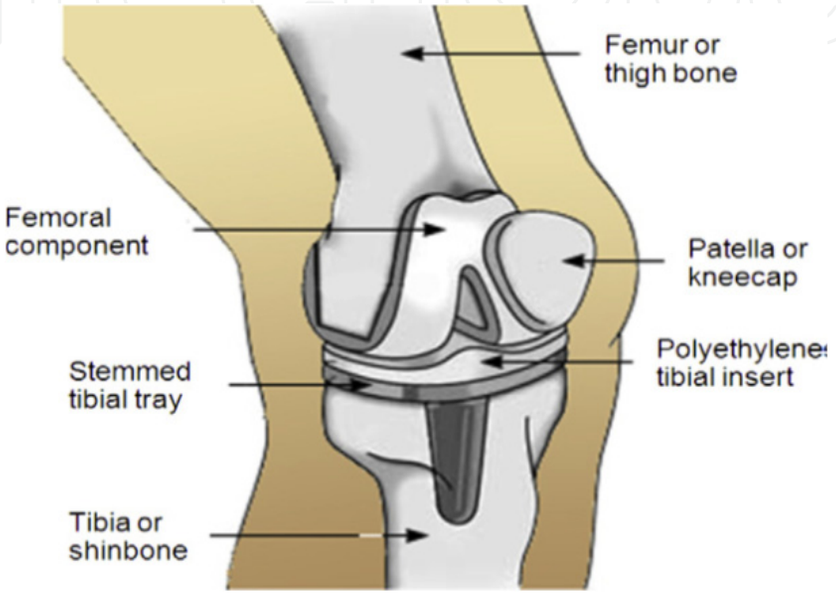


Figure 8. Total knee replacement components (Bahraminasab and Jahan 2011)

4.2. Biomaterial requirements for femoral component

Implant materials must balance some requirements which are essential for prosthesis to have well performance with no rejection after long term use in the body. These requirements vary from one application to another. The required properties for femoral component of TKR include strength, elastic modulus, ductility, density, corrosion and wear resistance, biocompatibility and osseointegration (Bahraminasab and Jahan 2011). High strength is required to avoid fracture of the component, and ductility is, also, needed to avoid brittle failure of the implant under loading conditions. Furthermore, the weight and density of the biomaterial must be comparable to that of bone. Low elastic modulus plays an important role for heavily loaded joint such as TKR. Large difference between Young's modulus of implant component biomaterial and the adjacent bone can contribute to stress shielding effect, which causes the subsequent bone resorption and aseptic loosening. In addition to this, lower Young's modulus means higher damping capacity and resilience leading to more absorption of impact energy and dampening of the maximum stress between the bone and the articular implant. High corrosion resistance is, also, desirable due to the corrosive body fluid. The metallic implants release unfavorable (non-biocompatible) ions that either can accumulate in tissues, near the implant, or they might be transported to the other parts of

the body (Okazaki and Gotoh 2005) causing toxic effects. Low wear resistance or high coefficient of friction between the articular surfaces can result in aseptic loosening of the component. Furthermore, wear debris is biologically active and provides adverse inflammatory response, which destruct the healthy bone supporting the actual prosthesis. Osseointegration refers to the bone healing process. The incapability of the implant surface to bond with the adjoining bone and tissues leads to micro-motions and formation of a fibrous tissue around the implant promoting aseptic loosening process (Viceconti, Muccini et al. 2000; Geetha, Singh et al. 2008). The biocompatibility for total joint replacements has been defined as; optimizing the rate and quality of bone apposition to the material, minimizing the release rate of corrosion and the tissue response to the released particles, minimizing the release rate of wear debris and the tissue reaction to this debris, and optimizing the biomechanical environment to minimize disturbance to homeostasis in the bone and its surrounding soft tissue (Williams 2008). Among the above described properties, resistance to wear, low elastic modulus and acceptable osseointegration are the necessities avoiding aseptic loosening problem.

4.3. Superiority of NiTi compared to the current materials

NiTi alloys combine high strength, unique fatigue resistance, and good ductility (Bahraminasab, Hassan et al. 2010). These materials exhibit high resistance to wear even more than Co-Cr-Mo alloy (the most accepted current material for femoral component). The wear resistance in conventional materials depends upon some mechanical factors such as hardness, toughness, and work-hardening. However, for NiTi shape memory alloys, other parameters are believed to be the reasons for high wear resistance and low coefficient of friction such as the recovery of the superelastic deformation (Yan 2006), pseudoelasticity effect and strength (Abedini, Ghasemi et al. 2009). Further, the low Young's modulus of this alloy also decreases the maximum contact pressure and accordingly the wear rate (Yan 2006). High wear resistance of this material makes it a potential for the applications such as femoral component of TKR or components of other joint replacements in which wear is of crucial importance. Most of wear tests carried out on NiTi were pin-on-disk tests with NiTi disk and steel bearing pin. However, in the knee joint prosthesis femoral condyles (made of metals) articulate against the tibial tray (made of UHMWPE), thus; it is required to obtain the coefficient of friction between NiTi and UHMWPE. To the best of the authors' knowledge, the values of friction coefficient and wear rate between these two materials have not been reported in the literature. Knee joints function as dynamically loaded bearings that are subjected to 10^8 loading cycles in 70 year lifetime. The average friction coefficient of the load bearing synovial joints including hip and knee is around 0.02 and the wear factor is approximately 10^6 mm^3/N. However, the coefficient of friction for materials implanted in the body varies between 0.05 to 0.16, which depends on the mate material and the type of test lubricant (Geetha, Singh et al. 2008). Therefore, it would be interesting to test this material against UHMWPE (or XLPE) to obtain the friction coefficient and wear rate in the conditions mimicking the natural knee joint situations and to have a precise comparison with the existing materials. On the other hand, low stiffness or low Young's modulus of NiTi, which is much lower than those of Co-Cr based alloys and stainless steels and

much closer to that of bone (less than 30 GPa), minimizes the stress shielding effect and the subsequent aseptic loosening. It also means higher damping capacity and resilience, which can highly affect the absorption of impact energy and reduce the peak stress between the bone and the articular prosthesis (Bahraminasab and Jahan 2011). Another issue that is worth to be highlighted is the superelastic behavior. Human body especially the skeletal part is subjected to stresses during daily activities such as walking, stair climbing and lifting objects. The stresses experienced by the bone vary from one activity to another, and also vary at different time during an activity. These stresses will cause deformation and change the shape, thus it is important that once an activity is completed, the implant return to its designated shape. The elastic property ensures this but over a long period of use, superelastic behavior of NiTi shape memory alloy may help for longer implant life (no unrecoverable or residual strain). In addition to the dense or bulk NiTi, porous form of these alloy have very high potentials to be used in orthopedics because the interconnected open pores and large surface area enables the body fluids transportation and accelerates the healing process. Furthermore, it also allows tissue and bone cells in-growth, which makes strong anchorage between the prosthesis and the adjoining bone, provides long-term fixation, and reduces knee implant aseptic loosening. Porous NiTi alloy, therefore, presents better osteoconductivity and osteointegration than bulk NiTi alloy. Appropriate amount of porosity and pore size, and suitable fabrication technique make it possible to obtain a combination of good contact between bone and implant, high strength, low elastic modulus, high toughness and high energy absorption (Ryhanen, Niemi et al. 1997; Zhu, Yang et al. 2008). It is possible to achieve low stiffness in the range of bone elastic modulus to minimize stress shielding effect, and provide high damping capacity. This material may offer other advantages such as super-elasticity after tissue in-growth, superb mechanical stability within the host tissue because of shape-recovery characteristic, and morphology similar to that of bone. Figure 9 shows a comparison of NiTi and trabecular bone porosity.

To the best of authors' knowledge, NiTi has not been used for prosthetic femur, however, based on finite element analysis (FEA) study and multi-criteria decision-making (MCDM) method, these materials are superior to the currently used metallic materials for this application (Bahraminasab and Jahan 2011; Bahraminasab, Sahari et al. 2011). MCDM is usually used for contemporary materials selection problems in which the suitability of candidate materials is assessed against multiple criteria rather than considering one single factor (Jahan, Ismail et al. 2010) to avoid misuse of materials and the respective huge cost. The MCDMs approaches have been developed for biomedical applications (Jahan, Bahraminasab et al. 2011; Jahan, Mustapha et al. 2011) among which comprehensive VIKOR method (Jahan, Mustapha et al. 2011) was used to select the best material for femoral component of TKR. Based on the results of the evaluation, porous NiTi (SMA) was the optimal metal alternative with the confidence level of 100% and dense NiTi (SMA) was ranked second with the confidence level of 73 %. The compositions of the current and promising metals considered for MCDM material selection and comparison of their properties are given in Table 1 and Table 2 respectively. FEA allows changing material properties of the mechanical components and predicts the performance before manufacturing any prototypes. A finite element analysis study on the knee joint under static

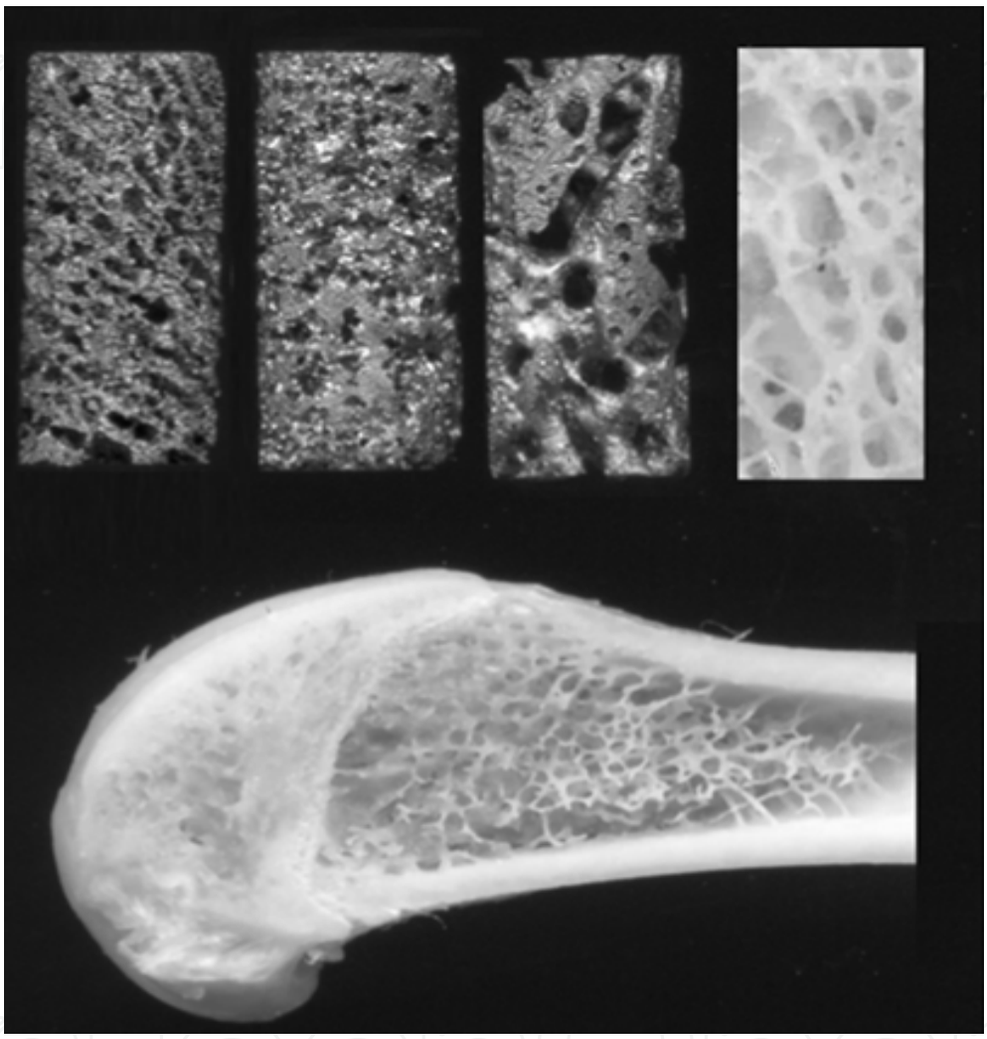


Figure 9. Porous NiTi compared with trabecular bone (taken from http://herkules.oulu.fi/isbn9514271246/html/c721.html)

load of 800 N at 0° of flexion angle demonstrated that NiTi (SMA) provided higher Von Mises stresses on the femoral bone than Co-Cr and Ti-6Al-4V alloys, as shown in Figure 10 and Figure 11, meaning that this material can reduce the stress shielding, and consequently aseptic loosening of the implant (Bahraminasab, Sahari et al. 2011). FEA and MCDM partly covered the theoretical aspects related to the use of NiTi as femoral component. However, there is a long distance from theoretical development of biomaterials to the practical applications including in vivo and vitro tests.

Materials number	Materials' names	Compositions
1	Stainless steel L316 (annealed)	Fe balancing, 17-20% Cr,10-14%Ni, 2-4% Mo, 0.03-0.08% C, 2% Mn and 0.75% Si
2	Stainless steel L316 (cold worked)	
3	Co-Cr alloys (Wrought Co-Ni-Cr-Mo)	Co balancing, 19-21% Cr, 9-11% Ni, 14.6-16%W, 0.13% Mo, 0.05-0.15 %C, 0.48%Si and maximum 2%Mn &3%Fe
4	Co-Cr alloys (Cast able Co-Cr-Mo)	Co balancing, 27-30% Cr, 2.5% Ni, 5-7% Mo, 0.75%Fe, 0.36%C and maximum 1%Mn &Si
5	Ti alloys (Pure Ti)	0.3% Fe, 0.08% C, 0.13% O2, 0.07% N2
6	Ti alloys (Ti-6 Al-4V)	Ti balancing, 5.5-6.5% Al, 3.5-4.5% V, 0.25% Fe and 0.08% C
7	Ti-6Al-7Nb (IMI-367 wrought)	Ti balancing, 5.50 - 6.50 % Al, <= 0.080 % C, <= 0.0090 % H, <= 0.25 % Fe, 6.50 - 7.50 % Nb, <= 0.050 % N, <= 0.20 % O, <= 0.50 % Ta
8	Ti-6Al-7Nb (Protasul-100 hot-forged)	
9	NiTi shape memory alloy	Ni 55.0 - 56.0 %, Ti 43.835 - 45.0 %, C <= 0.050 %, Fe <= 0.050 %, O <= 0.050 %, H <= 0.0050 %, Other <= 0.010 %
10	Porous NiTi shape memory alloy	Ni–49.0at.%Ti, 16% porosity

Table 1. Candidate materials for femoral component and their compositions

Material number	Density (g/cc)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation (%)	Corrosion resistance	Wear resistance	Osseointegration
1	8	517	200	40	high	Above average	Above average
2	8	862	200	12	high	Very high	Above average
3	9.13	896	240	10-30	Very high	Extremely high	High
4	8.3	655	240	10-30	Very high	Extremely high	High
5	4.5	550	100	54	Exceptionally high	Above average	very high
6	4.43	985	112	12	Exceptionally high	High	very high
7	4.52	≥ 900	105 – 120	≥ 10	Exceptionally high	High	very high
8	4.52	1000-1100	110	10-15	Exceptionally high	High	very high
9	6.50	≥1240	≥48	12	Extremely high	Exceptionally high	Average
10	4.3<	1000	15	12	Very high	Exceptionally high	Exceptionally high

Table 2. Properties of candidate materials

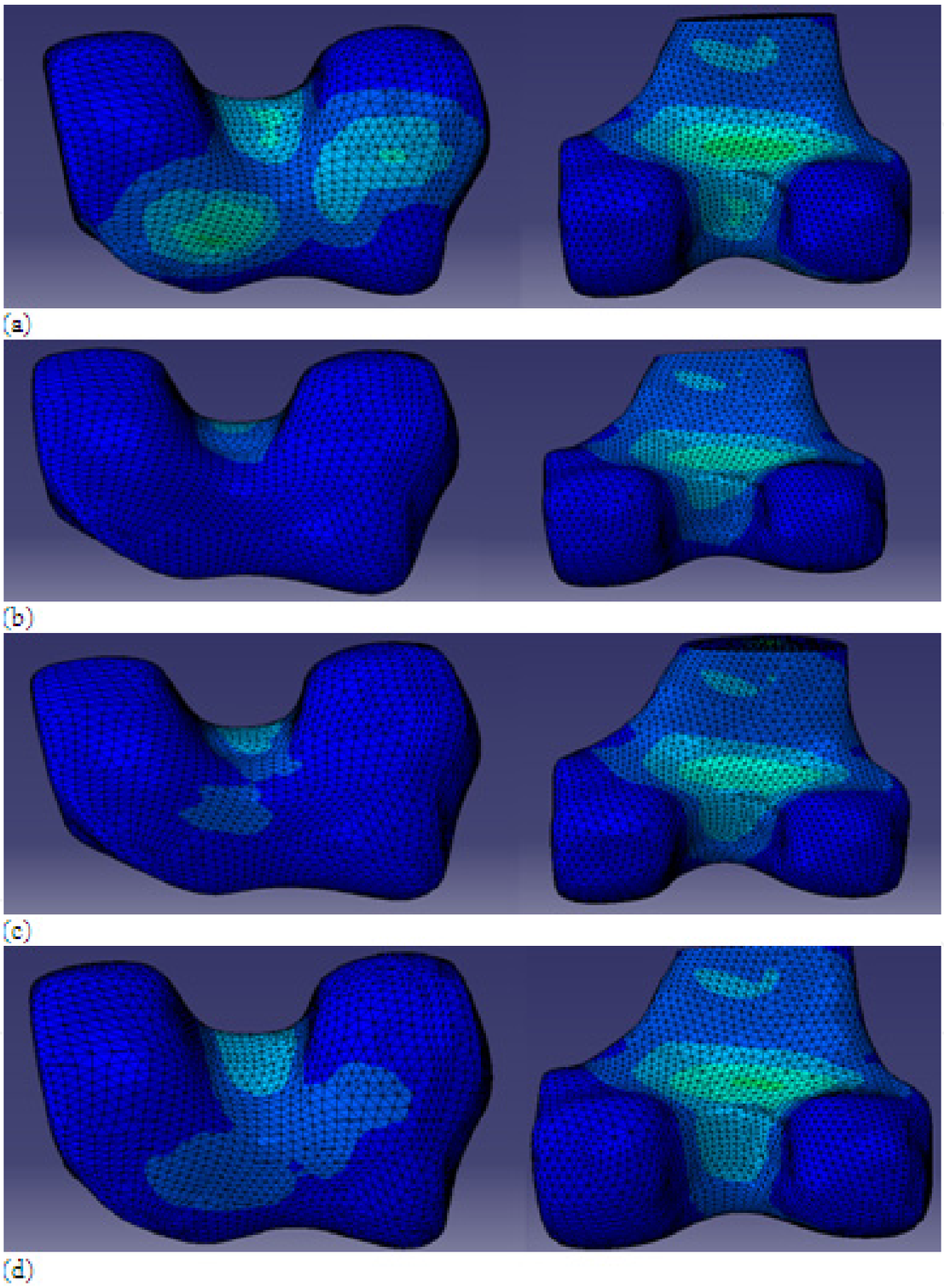


Figure 10. Stress pattern on the femur for (a) natural knee (b) Cr-Co alloy (c) Ti-6Al-4V (d) NiTi (SMA)

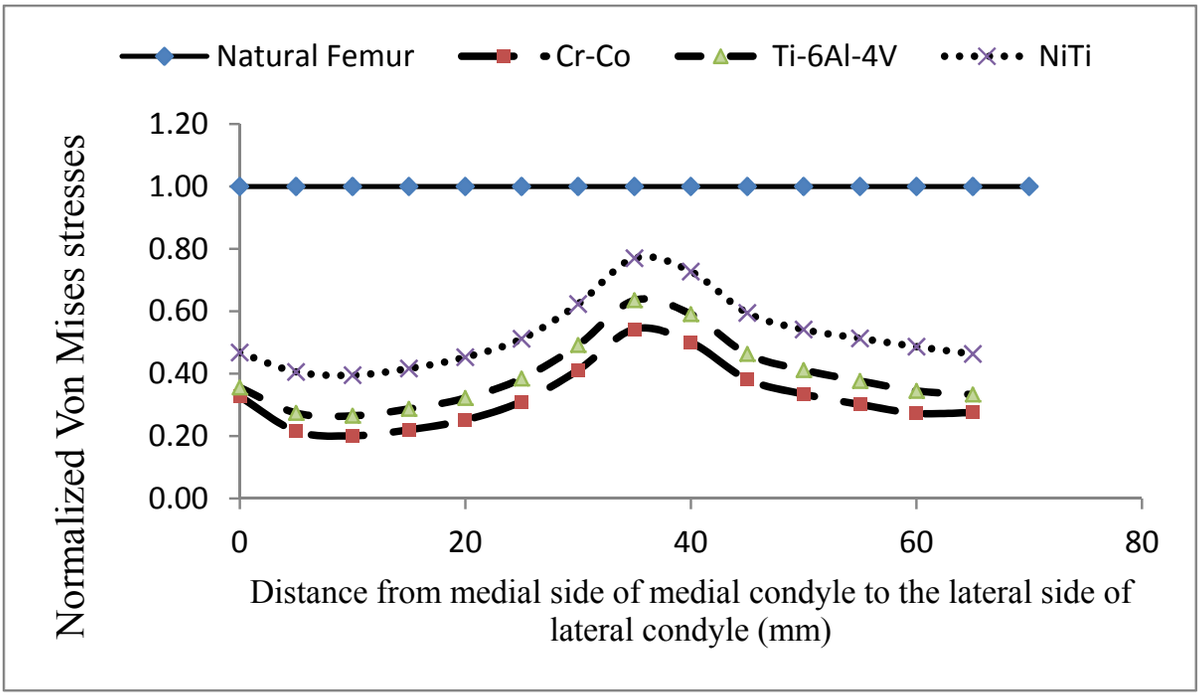


Figure 11. Comparison of stress values for natural femur, Cr-Co alloy, Ti-6Al-4V and NiTi at 30 mm posterior to anterior

5. Discussion

Development and selection of optimal biomaterials for orthopedic applications is a challenging task due to dealing with complex biological and mechanical requirements on one hand, and growing number of damaged organs replacements with synthetic materials on the other hand. Shape memory alloys, particularly NiTi alloys have been considered for many orthopedic applications either in practice or as promising material for future use. There are several main aspects of NiTi that favor its use as implant materials. These include biocompatibility (especially corrosion resistance), the ability to return to its original shape at a specific temperature, and material property values comparable to those of natural bone. Most of in vivo investigations on NiTi implantation and in vitro experiments demonstrated good biocompatibility of this material. Furthermore, higher level of biocompatibility also can be achieved by surface modification of NiTi alloys. The ability of NiTi to restore its original shape (after deformation) at a specific temperature makes the material suitable for a wide range of applications; we recall the staples, plates for fractured bone and gloves for physiotherapy. Additionally, the superelastic behavior of this material may provide benefits for human skeletons, especially for joint replacements where it is subjected to cyclical stresses during daily activities. The closeness of the implant and the natural bone material properties (elastic modulus), particularly at the interface reduces the stress difference between these two parts and hence decreases the stress shielding effect. Therefore, it appears that NiTi SMA is a very suitable candidate for orthopedic implant applications, among which several have been well established but some other suggested applications, such as femoral component of total knee replacement, require more investigations and

preclinical tests. Co-Cr based alloy, which currently is the most accepted material for prosthetic femur, and other metals including Ti and its alloys and stainless steel cannot completely fulfill the desired requirements for long term use in the body, and the revision surgery is usually performed 10-15 years after the implantation of knee prosthesis. Therefore, there is still a need for material solution in knee joint replacement. However, applying a new biomaterial for a specific application may impose either redesign of the component or material tailoring for the existing design. Both bulk and porous NiTi are high potential materials in orthopedic applications such as this. Bulk NiTi has high wear resistance and fairly low elastic modulus, which are the two important properties to avoid aseptic loosening of femoral component, but unfortunately, it lacks osseointegration and bioactivity. To overcome this deficiency, surface engineering are being conducted on this material. Generation of porosity in material structure is also a way to obtain bioactivity and well integration with the bony bed, which simultaneously can further reduce the elastic modulus as well. Porous NiTi, therefore, is a quite high potential material for this application. However, when the porosity increases, corrosion behavior of NiTi requires careful consideration. Porous NiTi has many orthopedic applications including spinal fixation, acetabular hip prostheses, and permanent osteosynthesis plates.

For using a biomaterial for knee joint prosthesis, several medical and engineering skills are needed. Knowledge on the anatomy of the natural knee joint, the histology of cortical and cancellous bone, cartilage, meniscus, ligament, tendon and synovial fluid, the physiology of circulation and of the bone growth and bone loss, the biomechanics of the knee joint during daily activities, orthopedic implantation methods, pathology (e.g. osteoarthritis and osteoporous) and biocompatibility are all the essential medical skills. The engineering skills include tribology, kinematics, fracture mechanics, fatigue and elasticity/plasticity theory. Therefore, a multidisciplinary team of surgeons and materials scientists and engineers are needed for new material applications in total knee replacement. Generally, the requirements for femoral component may necessitate for the components of other joint replacement with similar mechanical and biological conditions. However, it should be pointed out that the required properties are site specific in human body, and in selection process of materials for different joints, the alterations must be carefully taken into account. NiTi as a promising material can be widely investigated theoretically and clinically, as a future research, in biomedical engineering especially for orthopedic applications.

6. Conclusion

From the above discussion, the following conclusions can be made:

1. NiTi shape memory alloy is a biocompatible material with low elastic modulus and high wear resistance which makes it suitable for use in orthopedic applications, particularly joint replacements such as knee and hip.
2. NiTi SMA has a unique property to “remember” its shape at a specific temperature and return to that shape when the specific temperature is reached. This property provides

advantages for use in human body as an artificial organ since the human body experiences stress changes during activities.

3. NiTi SMA has relatively low Young's modulus, and it can be reduced by generation of porosity in the structure to be comparable with that of bone which results in lower stress difference between the implant and bone or stress shielding effect, and hence, increase the implant life.
4. Porous NiTi not only offers elastic modulus in the range of human bone modulus, but also promotes the growth and penetration of bone cells and tissues into the implant and therefore provides strong anchorage, avoiding loosening of the implant.

Author details

Marjan Bahraminasab and Barkawi Bin Sahari
Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, Malaysia

Barkawi Bin Sahari
Institute of Advanced Technology, ITMA, Universiti Putra Malaysia, Malaysia

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