Mechanical Aspects Of Metallic Biomaterials In Human Hip Replacement

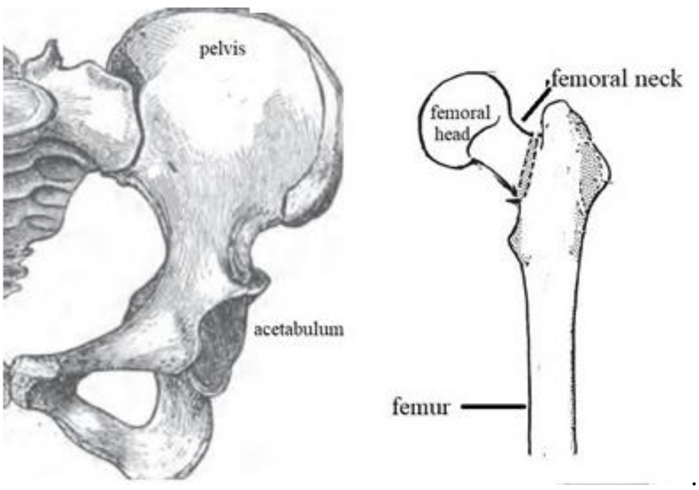
[1]Arun Kumar Sharma, [2]Dr. Rakesh Bhandari, [3]Dr.Amit Aherwar
[1]Research Scholar, [2]Associate Professor, [3]Assistant Professor
[1] Mechanical Engineering Department
[1]Sangam University,Bhilwara,India

Abstract : The significance of total hip replacement is due to continuous improvement in population and ageing people who are in pursuit of high-quality life. If there is any malfunctioning in hip joint, the reason of which may be the hip fracture, osteoporosis, and injury due to recurrent falls in old age, hip replacement is the perfect solution. Total hip replacements enhance the motile and gratification of life of the patient by mitigating pain and disability. The material which used in total hip replacements should have excellent properties in the term of, resistance to fracture, mechanical, corrosion resistance, high strength, reliable in load bearing and wear resistance which became the cause of great lifespan for the implant as well as compatibility inside the body. Due to these reasons, Metallic materials are very suitable for the hip implant. Continuous research to obtain improved biomaterials for excellent performances is going on worldwide. The standard lifespan of human increases so the requirement of the excellent lifespan of the implant also highly increased due to this reason the material, which used for implants, required improvement in properties of materials. This article focuses on the discussion of mechanical aspects of metallic biomaterials which used for human hip joint replacement. Specific metallic biomaterials made from stainless steels, alloys of cobalt, discussed in this article.

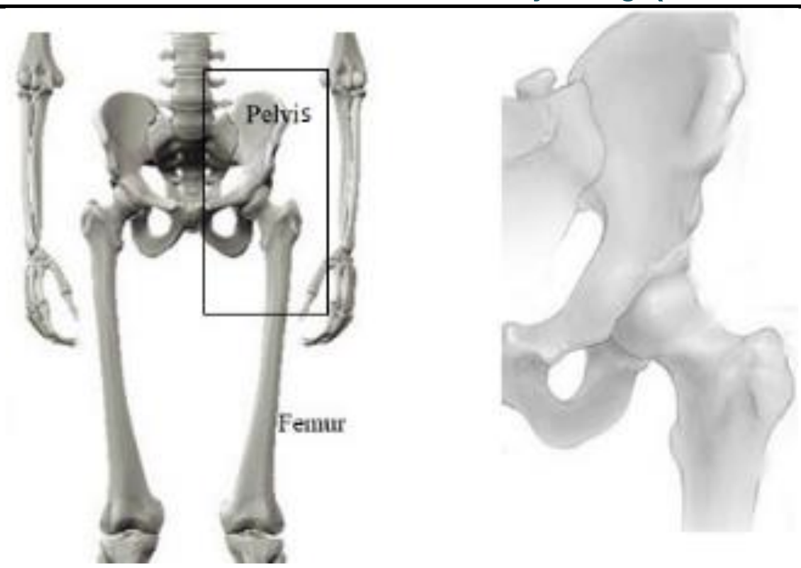
Keywords - Biomaterials, Hip Joint ,Co-Cr alloys, Mechanical, Stainless Steel, Ti alloys

Introduction

Total hip replacement in human is an effective procedure in surgery [1]. The human hip joint is synovial joint, and this is ball and socket arrangement type stable weight bearing joint. The ball-shaped head fits in the acetabulum which is a socket in the pelvis, so the ball considered as femoral head, the acetabulum as the socket, this configuration is the root of its inherent strength due to this hip joint can bear large forces, if there is some disorder in this arrangement, it may be the cause of exceptional stresses throughout the joint cartilage and bone which may be the cause of degenerative arthritis which leads to further damage of hip. The space in a joint cavity of synovial joints filled with the fluid known as the synovial fluid, it is for lubrication, which results, greater mobility and reduction of friction in between bones [2,3,4]. Joint has the high range of internal and external motion; extension, abduction, flexion, adduction is due to triaxial motion. A standard hip joint works correctly in almost all type of motion required for everyday activities like moving sitting, bending meanwhile acetabulum aligned adequately with the femoral head [5]. The shape of a femoral head is similar to sphere and size is around 20 to 30mm radius which varies with the weight of the body, this is key of the transmission and absorption of stress due to weight bearing, to the femoral neck's dense cortical bone [6].



(a)



(b)

Figure 1: (a) Individual components for Hip Joint. (b) Hip Joint in THR [50]

Bone is critical for the human as it supports body weight. Before development as well as the application of a new biomaterial for bone replacement the function of bone tissues and about bone tissues at various scale level should understand precisely as Bone having a very complicated structure which may be described as hierarchical and anisotropic tissues due to this a noticeable difference found in mechanical properties, microstructure and other related function between bone and artificial material. Fracture toughness, fatigue strength, ductility, ultimate strength, stiffness and yield strength are essential properties of bone. Femoral head, femoral stem, liner and the acetabular shell are components of the artificial hip implant. [7,8].

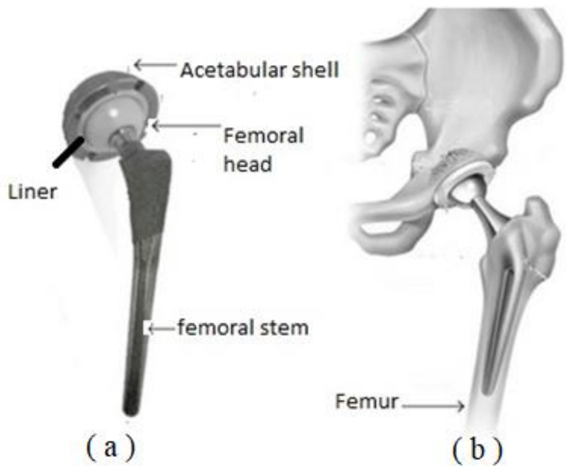


Figure 2: (a) The artificial Hip Joint Components (b) Placed Components [51]

Metallic Biomaterials

Widely used metallic biomaterials are Ti-based alloys, stainless steel and Co-Cr alloy. The materials must have biocompatible, good resistance to wear and corrosion, strong resistance to fatigue, and reasonably priced which used in Total hip replacement. Metallic biomaterials generally used in orthopedic applications especially for joint replacements because of excellent mechanical properties [9].

Biocompatibility is the performance of material which is intended to use in close interaction with living tissue material should have properties like, non-cytotoxic, not releasing harmful materials, not causing adverse reactions, including allergic and inflammatory reactions with host tissues, organs [10,11].

(1) Co-Cr alloys

Co-based alloy developed the early 1900s, in 1930 a cast alloy based on Cobalt-Chromium-Molybdenum known as Vitallium (Co-28Cr-6Mo), developed and used for the prosthetic acetabular cups until 1960, in 1960 total replacement operation introduced and in early 1960 other Co-Cr alloys developed [12-17].

Co-Cr alloy recognized for great corrosion resistance and its wear resistance well known because it is superior to the other metallic biomaterial. In, hip artificial joint wear resistance property is essential especially in sliding parts of hip joints [18-

21]. Mechanical properties like ductility, strength of Co-Cr alloy may be changed by adding an alloying element and by thermomechanical treatment. Addition of Zr to cast Co-28Cr-6Mo alloy will enhance tensile strength as well as elongation. If the addition of the maximum acceptable value of nitrogen less than 0.10 mass%, it increases workability, elongation and mechanical strength [22-26].

Mechanical properties illustrated in fig 3, of Co-Cr alloys, generally used for hip replacement.

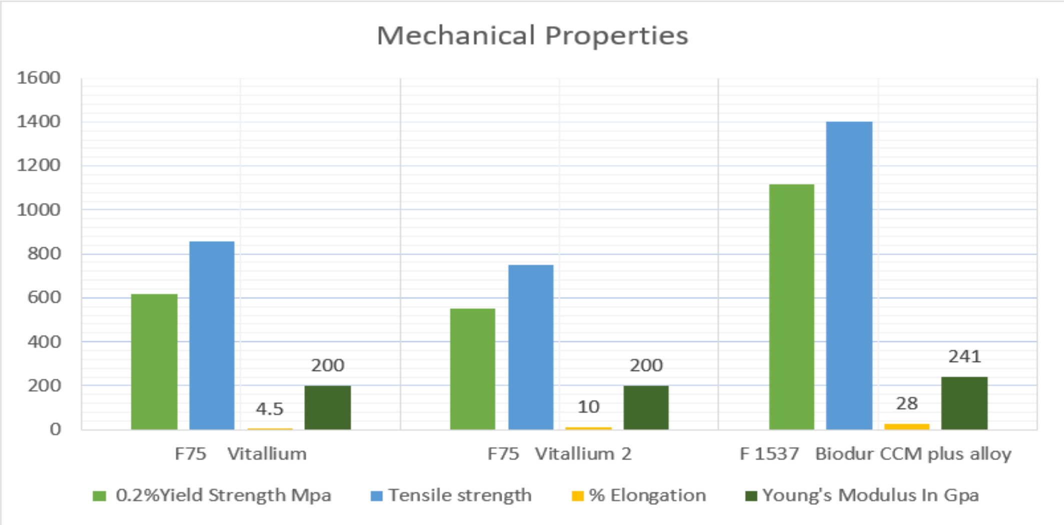


Fig 3 : Mechanical Properties (Co-Cr Alloys)[52-53]

(2) Ti-Based alloys

Titanium and alloys of titanium are well-accepted biomaterials for biomedical applications by cause of excellent biocompatibility, exceptional mechanical strength, superior corrosion resistance, the lower value of elastic modulus and lower weight density as in compared with alternative metallic biomaterials. [27-30].

According to microstructure Titanium alloy may be divided as α-type titanium alloys and ß-type titanium alloys and (α + ß)-type titanium alloys. ß titanium alloys generally used in total hip replacement. ß alloys have higher strength, low elasticity modulus and good resistance toward corrosion hence used as the biomaterial for hip joint [31-35].

The modulus of elasticity for ASTM standard biomedical titanium alloys such as for Ti-6Al-4V is 100-110Gpa. and for Ti-12Mo-6Zr-2fe is 74-85GPa. while for Ti-35Nb-7Zr-5Ta is 55Gpa. Addition of zircon in titanium results increased elongation and fatigue strength.Ti-6Al-4V used in femoral stems, heads, as well as femoral components while Ti-5Al-2.5Fe and Ti-Al-Nb used in Femoral stems, heads [36]. According to the value of modulus of elasticity, rigidity can decide, the high value of modulus of elasticity shows the high rigidity or vice versa. The material used in hip replacement, generally having high young modulus than bone due to this difference stress shielding which is known as a reduction in bone density can occur in hip implants, which diminished the life of implant because of a difference in stiffness between implant material and bone [37,38].

Fig 4, depict mechanical properties of stainless steel which generally used in hip replacement.

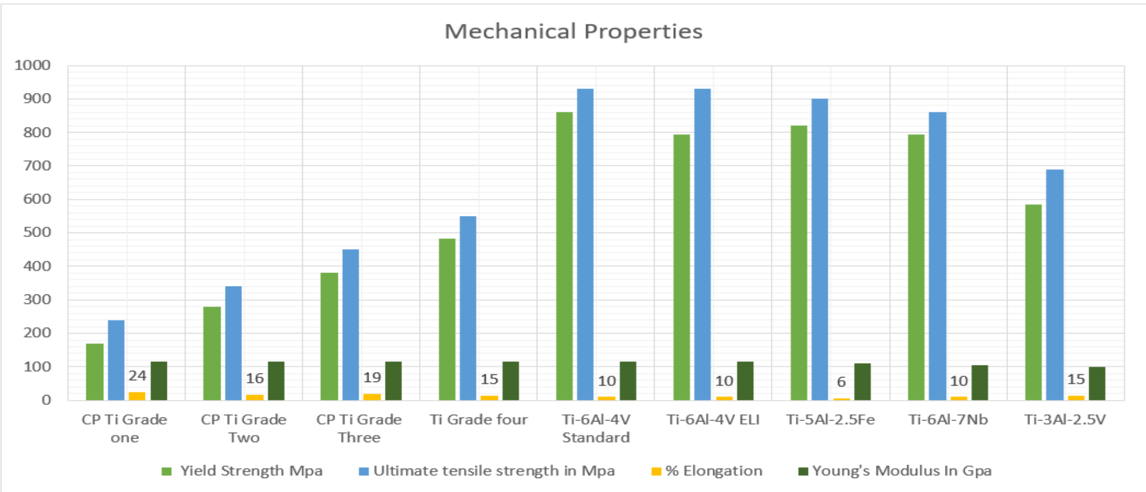


Fig 4 : Mechanical Properties(Ti Alloys) [54-55]

(3) Stainless steel

In 1938 the first stainless steel total hip replacement used and it is the source of the idea for the total hip replacement [39]. Stainless steels may be divided in chromium type and chromium-nickel type steels in consonance with chemical compositions and according to microstructure, ferrite (BCC) and austenite (FCC)[40].

Chromium-Nickel type austenitic stainless steels used for biomedical application especially in orthopedic which contain Cr (17-20 %), Mo (2-3 %), Ni (12-15 %) and other materials which are in a very small amount. A316L stainless steel used for orthopedic applications, which containing good ductility and high strength Because structure of unit cell is FCC. This steel containing Carbon percentage below 0.03% [41-44]. Nickel ions released by this steel in body which produce very harmful effect in human body which can result as allergy, pain or even cancer. Nitrogen steel is the solution to this problem, this steel having sufficient corrosion resistance and strength, which is higher in comparison of Ti alloy. The nitrogen percentage should be below 0.9% which become the reason to avoid brittleness in this steel. Otherwise, brittleness will increase [45,46,47,48,49].

Fig 5 illustrates the mechanical properties of widely used stainless steel for human hip replacement.

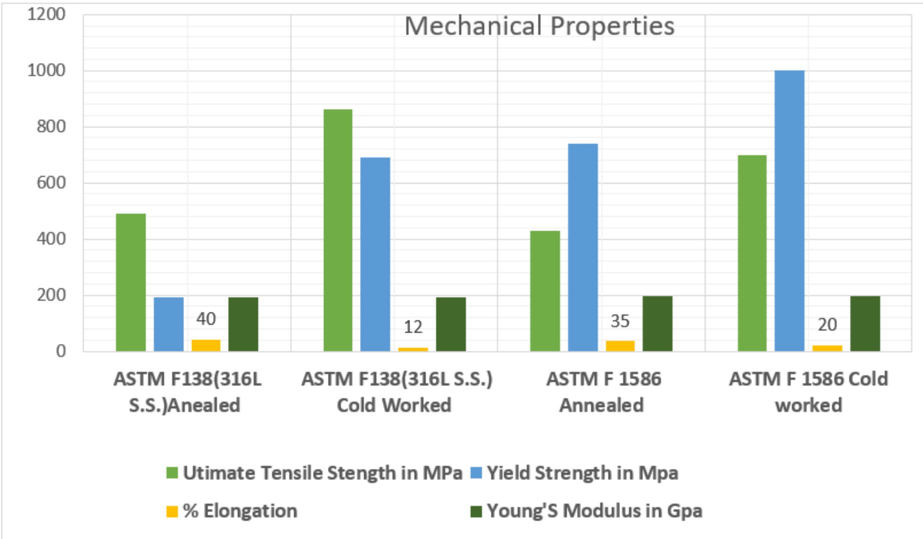


Figure 5: Mechanical Properties (Stainless Steel) [56]

Conclusion

This study compared the mechanical properties of different metallic biomaterials as well as suitability for use in biomedical applications which also includes mechanical biocompatibility and biological biocompatibility of implant. The lifespan of metallic biomaterials based implants is around the 20-25years, and after 15 years failure can occur. So it is an essential requirement for research of materials, which can work perfectly in line with human lifespan, especially for hip replacement. The failure of an implant in a human body may be due to wear, corrosion, low fracture toughness, inflammation, low fatigue strength, a big difference in modulus of elasticity in bone and implant material so these factors generally considered in the selection of material for orthopedic implant in the human. For total hip replacement, metallic biomaterials are the best option. Interdisciplinary research is essential for the biomaterial required for orthopedic implants because, in the human body, the demand of the Biomedical implant is increasing continuously. Still, the failure rate of the implant is high.

References

[1] Marjan Bahrami Nasab, Mohd Roshdi Hassan and Barkawi Bin Sahari.2010.Metallic Biomaterials of Knee and Hip – A Review, Trends in Biomaterials & Artificial Organs Vol 24(2), pp 69- 82.
[2] C. H. Wilson.1990. Clinical Methods: The History, Physical, and Laboratory Examinations, 3 ed., H. W. H. J.Walker HK, Ed., Boston: Butterworth.
[3] C. M. Larson, J. Swaringen and G. Morrison.2005.A Review of Hip Arthroscopy and its Role in the Management of Adult Hip Pain, The Iowa Orthopedic Journal, vol. 25, pp. 172-179.
[4] Backman, S.1957.The proximal end of the femur. Acta Radiol. Suppl. 146.
[5] R.G. Tronzo.1984. Surgery of the Hip Joint volume I , Springer-Verlag, New York.
[6] Koval K.J. Zuckerman J.D.2000. Anatomy. In: Hip Fractures. Springer, New York, NY.
[7] Burr DB, Allen MR.2014. Basic and applied bone biology. Academic press, New York.
[8] Sebastian Bauer a , PatrikSchmuki a, , Klaus von der Mark b , Jung Park.2013.Engineering biocompatible implant surfaces Part I: Materials and surfaces, Progress in Materials Science 58, 261–326.
[9] M.H.AhmedJ.A.ByrneT.E.KeyesW.AhmedA.ElhissiM.J.JacksonE.Ahmed.2012.Characteristics applications of titanium oxide as a biomaterial for medical implants. The Design and Manufacture of Medical Devices Woodhead

Publishing Reviews: Mechanical Engineering Series Pages 1-57.

[10]Sinno H, Tahiri Y, Gilardino M, Bobyn D.2010.Engineering alloplastic temporomandibular joint replacements. McGill J Med ,13:63–72.

[11]Peters K, Unger RE, Kirkpatrick CJ.2009.Bio-medical materials. In: Narayan R, editor. Biomedical materials. First edition. New York: Springer; p. 1–566.

[12]Beltran AM.1987. Cobalt-base alloys. In: Sims CT, Stoloff NS, Hagel WC (eds) Superalloys II. Wiley,new York, pp 135–163.

[13]Morral FR.1966.Cobalt alloys as implants in humans. J Mater 1:384–412 .

[14]Morral FR.1968. The metallurgy of cobalt alloys - a 1968 review. J Met 20(7):52–59.

[15]Venable CS, Stuck WG, Beach A .1937.The effects on bone of the presence of metals; based upon electrolysis. Ann Surg 105:917–938.

[16]Venable CS, Stuck WG .1943. Clinical uses of Vitallium. Ann Surg 117:772–782.

[17]http://www.sciencemuseum.org.uk/broughttolife/objects/display.aspx?id=4899.

[18]Narushima T, Mineta S, Kurihara Y, Ueda K .2013.Precipitates in biomedical Co-Cr alloys. JOM 65:489–504.

[19]NarushimaT .2010.New-generation metallic biomaterials. In: Niinoni M (ed) Metals for biomedical devices. Woodhead, Cambridge, pp 355–378.

[20]Niinomi M, Hanawa T, NarushimaT .2005.Japanese research and development on metallic biomedical, dental, and healthcare materials. JOM 57(4):18–24.

[21]Aherwar, Amit; Singh, Amit Kumar; Patnaik, Amar.2016. Cobalt Based Alloy: A Better Choice Biomaterial for Hip Implants, Trends in Biomaterials & Artificial Organs . Vol. 30 Issue 1, p50-55.

[22]Lee S-H, Uchikanezaki T, Nomura N, Nakamura M, Chiba A.2007. Effects of zirconium addition on microstructures and mechanical properties of Co-29Cr-6Mo Alloy. Mater Trans 48:1084–1088.

[23]Mori M, Yamanaka K, Matsumoto H, Chiba A.2010. Evolution of cold-rolled microstructures of biomedical Co–Cr–Mo alloys with and without N doping. Mater Sci Eng A 528:614–621.

[24]Chiba A, Lee S-H, Matsumoto H, Nakamura M.2009.Construction of processing map for biomedical Co-28Cr-6Mo-0.16N alloy by studying its hot deformation behavior using compression tests. Mater Sci Eng A 513–514:286–293.

[25]Dempsey AJ, Pilliar RM, Weatherly GC, Kilner T.1987.The effects of nitrogen additions to a cobalt-chromium surgical implant alloy. Part 2 mechanical properties. J Mater Sci 22:575–581.

[26]Yamanaka K, Mori M, Chiba A.2014.Effects of nitrogen addition on microstructure and mechanical behavior of biomedical Co–Cr–Mo alloys. J Mech Behav Biomed Mater 29:417–426. 3903.

[27]Niinomi M, Nakai M, Hieda J.2012.Development of new metallic alloys for biomedical applications. ActaBiomater 8:3888–3903.

[28]Niinomi M, Hattori T, Morikawa K et al.2002. Development of low rigidity β-type titanium alloy for biomedical applications. Mater Trans 43(12):2970–2977.

[29]Yamamuro T.1989.Patterns of osteogenesis in relation to various biomaterials. J Jpn Soc Biomater 7:19–23.

[30] Park JB, Lakes RS.1992.In: Biomaterials: an introduction. Plenum Press, New York.

[31]Kuroda D, Kawasaki H, Hiromoto S, Hanawa, Kuroda S, Kobayashi M, et al. 2003.Titanium 2003 science and technology. Wenham, Germany: Wiley-VCH Verlag, GMBH and Co. K GaA; p. 3174.

[32]Tang X, Ahmed T, Rack HJ.2000. J Mater Sci;35:1805–11.

[33]Qazi J, Marquart B, Allard LF, Rack HJ. 2005.Mater Sci Eng C 25:389–97.

[34]SakaguchiNobuhito, NiinomiMitsuo, Akahori Toshikazu, Takeda Junji, Toda Hiroyuki.2005. Mater Sci Eng C 25:370–6.

[35]Qazi J, Rack HJ.2003. Titanium 2003 science and technology, vol. 1. Weinhem, Germany: Wiley-VCH Verlag, GMBH and Co.KGaA; p.651.

[36]Geetha M, Singh AK, Gogia AK, Asokamani R. J.2004. Alloys Compd.384:131–51.

[37]Long, M.; Rack, H.J.1998. Titanium alloys in total joint replacement—A materials science perspective. Biomaterials, 19, 1621–1639.

[38]Niinomi, M.; Hattori, T.; Niwa S.2004. Material Characteristics and Biocompatibility of Low Rigidity Titanium Alloys for Biomedical Applications. In Biomaterials in Orthopedics; Yaszemski, M.J., Trantolo, D.J., Eds.; Marcel Dekker Inc.: New York, NY, USA, pp. 41–62.

[39]McKee, G. K., and Watson-Farrar J.1966. Replacement of arthritic hips by the McKee-Farrar prosthesis. J. Bone Joint Surg., 48B:245-259.

[40]Davis JR .2003. Handbook of Materials for Medical DevicesASM International, Materials park, Ohio, USA.

[41]Menzel J, Kirschner W, Stein G.1996. High nitrogen containing Ni-free austenitic steels for medical applications. ISIJ Int 36:893–900.

[42]Ilevbare GO, Burstein GT.2001.The role of alloyed molybdenum in the inhibition of pitting corrosion in stainless steels. Corros Sci 43:485–513.

[43]Torgerser S, Gilhuus-Moe OT, Gjerdet NR.1993.Immune response to nickel and some clinical observations after stainless steel miniplate osteosynthesis. Int J Oral MaxillofacSurg 22:246–250.

[44]Kanerva L, Forstrom L.2001.Allergic nickel and chromate hand dermatitis induced by orthopedic metal implant. Contact Dermatitis 44:103–104.

[45]Mudali UK, Dayal RK, Gnanamoorthy JB, Rodriguez P.1996.High nitrogen steels. Relationship between pitting and intergranular corrosion of nitrogen-bearing austenitic stainless steels. Mater Trans 37:1568–1573.

[46]Sumita M, Hanawa T, Teoh SH.2004.Development of nitrogen-containing nickel-free austenitic stainless steels for metallic biomaterials-review. Mater Sci Eng C 24:753–760.

[47]Yang K, Ren Y.2010.Nickel-free austenitic stainless steels for medical applications. Sci Technol Adv Mater 11:13.

[48]Newman RC, Lu YC, Bandy R, Clayton CR.1984.Proceedings of the ninth international congress on metallic corrosion, vol 4. National Research Council, Ottawa, p 394.

[49]Talha M, Behera CK, Sinha OP.2013.A review on nickel-free nitrogen containing austenitic stainless steels for biomedical applications. Mater Sci Eng C 33:3563–3575.

[50]Alfred R. Shands Jr. , Raymond G. Tronzo.1984. Surgery of the Hip JointVolume 1, Springer-Verlag New York.

[51]AmitAherwar, Amit Kumar Singh, Amar Patnaik.2016. Cobalt Based Alloy: A Better Choice Biomaterial For Hip Implants,TrendsBiomater. Artif. Organs, 30(1), 50-55.

[52]Qizhi Chen , George A. Thouas.2015. Metallic implant biomaterials, Materials Science and Engineering R 87 , 1–57.

[53]Bridgeport, D. A., Brantley, W. A. and Herman, P. F.1993.Cobalt-Chromium and Nickel-Chromium Alloys for Removable Prosthodontics, Part 1: Mechanical Properties. Journal of Prosthodontics, 2: 144-150.

[54]Niinomi, M., Nakai, M.2011. Titanium-based biomaterials forpreventing stress shielding between implant devices and bone. International Journal of Biomaterials , 836587 -10.

[55]Boyer, B., Welsch, G., Collings, E.W. 2007. Materials Properties Handbook: Titanium Alloys, fourth ed. ASM International ,790-810.

[56]Davis JR.2003. Handbook of Materials for Medical Devices, ASM International, Materials park, Ohio, USA.