Metals in Spine

Dimitri Tahal, Karthik Madhavan, Lee Onn Chieng, George M. Ghobrial, Michael Y. Wang

Key words
- Alloys
- Metal implant
- Metals
- Spine surgery

Abbreviations and Acronyms
CoCr: Cobalt chrome
MRI: Magnetic resonance imaging
Ss: Stainless steel
Ti: Titanium

Department of Neurosurgery, University of Miama, Florida, USA

To whom correspondence should be addressed: Karthik Madhavan, M.D.
[E-mail: drkarthik19@gmail.com]

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The treatment of spinal disorders requires the consideration of a number of factors and understanding the type of material we are implanting is important. Alloys have different mechanical properties and behave differently under different physiologic conditions. Spinal implants need to have good performance in the characteristics of biofunctionality and biocompatibility. In this review, the alloys titanium, cobalt-chrome, nitinol, and tantalum will be examined closely. Several of the important properties that are considered when selecting an alloy for use in spinal instrumentation are explored and detailed for each. This allows for an assessment and comparison of each alloy and a possible determination of which is the best alloy for specific surgery or the best alloy for use in specific situations.

INTRODUCTION

Scoliosis is one of the oldest recognized spinal disorders, first described by Hippocrates. Over a period of time the treatment of spinal disorders has evolved with the introduction of fusions in 1931 by Hibbs and then the use of instrumentation made of different types of alloys.[1] The treatment of scoliosis is among the most complex of spinal disorders, requiring thoughtful consideration of numerous factors regarding surgical planning. We discuss the value of a thorough understanding of the different types of implant materials and their precise application to work in concert with various surgical interventions. Alloys have different mechanical properties and behave differently under different physiologic conditions. Treatment is also influenced by the age of the patient, nature and extent of spine pathology, and body habitus.[2]

Spinal implants need to have good performance in the characteristics of biofunctionality and biocompatibility.[3,4] Biofunctionality is concerned with the mechanical properties of alloys as it pertains to fulfilling the required function and consists of high yield strength, stiffness, and fatigue. Biocompatibility, on the other hand, refers to the presence or absence of an alloy's interaction with the internal environment of the human body, also referred to as *immunogenicity*. It is important to take into consideration all these characteristics to have a better outcome.

Just as it is important for a sculptor to choose and understand the stone to create a perfect statue, so does the deformity surgeon in selecting appropriate implant metal for a corrective measure. In this review, the alloys stainless steel (Ss), titanium (Ti), cobalt chrome (CoCr), nitinol, and tantalum are examined closely. Mechanical and nonbiomechanical properties that are considered when selecting an alloy for use in spinal instrumentation are explored and detailed for each. This allows for assessment and comparison of each alloy and a possible determination of which is the best alloy for specific surgery or the best alloy for use in specific situations.

TYPES OF METAL ALLOYS

Ss

Historically, Ss was commonly used for adult spine deformity for the past few decades. It is iron and carbon based. The primary alloy used for manufacture is the surgical 316L Ss with varying degrees of carbon, chromium, molybdenum, and nickel. The addition of molybdenum and lower carbon (L) content of the alloy provides superior corrosion resistance. Despite the lower cost of Ss, spine surgeons have shifted away from using it because of various mechanical and nonmechanical reasons (i.e., biofilm formation), which are discussed as follows.

Ti

Ti is the seventh most abundant metal in the world. Over the past few decades, Ss rods have been largely replaced by Ti rods due to superior mechanical and biologic properties.[5,6] Ti alloys are usually made of 90% elemental Ti and 10% aluminum and vanadium. Pure Ti has 2 different allotrophic phases, alpha and beta, based on their microstructure.[7] The alpha phase occurs below a temperature of 883°C and has a hexagonal close-packed crystalline structure. The beta phase occurs above the same temperature and has a body-centered cubic structure. Ti alloys are classified as alpha, near-alpha, alpha-beta, and beta alloys on the basis of the phase of Ti used. These microstructures are formed when the chemical composition is altered by combining with alloying elements through certain combinations of mechanical processing and heat treatment.[7-10] This freedom to adjust the microstructure allows Ti alloys to be tailored to suit desired mechanical properties.[11] The most commonly used Ti alloy is the Ti-6AL-4V (alloy with aluminium and vanadium), an alpha-beta alloy.

Cobalt Chrome

The use of CoCr alloys in spinal rods is relatively new. However, they have been used in gas turbines for their excellent strength and have been approved for use in joint replacement and dentistry for several decades.[12] CoCr alloy has gradually become more popular in the past decade due to its advantages over Ti alloy in strength.[5,13] The alloy consists of about 63% cobalt, 28% chromium, 5% molybdenum, and trace amounts of other elements such as manganese, silicon, iron, nickel, carbon, nitrogen, tungsten, phosphorus, sulfur, and boron. It is known to have high biocompatibility and good mechanical properties with high wear resistance.

Nitinol

Nitinol is an alloy composed of a near equiatomic mixture of nickel and Ti.[14] It began to be used in biomedical applications because it demonstrated optimal mechanical characteristics and biocompatibility while also exhibiting a remarkable ability dubbed as the "shape memory effect." It is now the most commonly used shape memory alloy of those available.[14-17] Nitinol has excellent fatigue resistance, superelasticity, good corrosion resistance, and high damping effect.

Tantalum

In solid form, tantalum has a high modulus of elasticity; therefore the porous form with a low modulus is used and avoids the stress-shielding effect. The structure of porous tantalum metal yields a high-volumetric porosity with an appearance similar to cancellous bone, a low modulus of elasticity, and relatively high frictional characteristics.[18] Tantalum is a metal with notable properties such as high ductility, biologic inertness, resistance to corrosion, a high level of biocompatibility, and ability to incorporate into a bony lattice.[19] Tantalum has been previously used in flexible stents, vascular clips, mesh, bone pins, and dental implants.[20-23] The downside to tantalum is that it is a rare metal with a high cost, and thus the rod end product is expensive.[24] For the most part, cheaper alternatives with acceptable overall properties have decreased the use of tantalum.

BIOMECHANICAL PROPERTIES

Fatigue/Breakage

The fatigue resistance of an alloy may be one of the most important properties because it determines how well and how long the spinal instrumentation can function without breaking down.[7] Many studies have been done assessing fatigue of certain alloys, but it is difficult to simulate the complex and varying in vivo environment in laboratory tests. These laboratory tests give an idea that can then be assessed in patients to check if it is reproducible in vivo.[25] The repetitive stresses typical of fatigue may lead to the formation of a crack, and this crack will grow until it reaches a critical size resulting in a fracture.[7,26] The formation of cracks typically occurs at stress concentration sites and at any type of surface imperfection that can occur from a defect in manufacturing or an acquired defect before it is implanted.

The fatigue resistance of Ti alloys is heavily dependent on its microstructure.[7,27-29] Fatigue and corrosion fatigue vary with the microstructure. Corrosion fatigue is the reduction of the fatigue life of an alloy when it is subject to corrosive forces. The fatigue life of a Ti alloy can also be improved by introducing surface compressive residual stresses or depositing a hard thin coating unto the surface. Nguyen et al[5,30] have shown that CoCr rods have a significantly larger fatigue lifespan than Ti rods in a simulated spinal fusion construct. In a recent clinical study comparing implant failure in 13 scoliosis patients, Shinohara et al[31] demonstrated a lower incidence of rod fracture in CoCr compared with Ti. However, the Ti connector fracture rate was higher when CoCr was used. The fatigue life of nitinol is not as straightforward as that of conventional metal alloys due to the nonlinearity of nitinol's superelasticity. One study reported excellent fatigue resistance under conditions of significant strain, while another reported much faster fatigue under stress-controlled situations of cyclic loading.[32-34] In the physiologic setting, a combination of stress- and strain-controlled conditions will be experienced; therefore there is still much research to understand the complicated fatigue characteristics of nitinol. No papers were found that directly addressed the fatigue properties of tantalum.

Elasticity/Hardness

Elasticity is the ability of a metal to deform and revert to its original shape. Young's modulus of elasticity describes the ability of a material to withstand up to a certain level of stress and strain and revert to its original shape. If stress or strain is applied greater than this maximum, then there is permanent deformation and at a certain point it will break. Ideally, the alloy of a spinal rod should have a modulus of elasticity similar to bone so that there is no stress-shielding effect.

Ti-6AL-4V, a widely used biomedical alloy, has a modulus of elasticity around 110 GPa while that of typical human bone is 30 GPa.[7,35] It is less ductile than bone, and this significant difference in stiffness/elasticity leads to an insufficient load transfer from the metallic implant to the bone tissue that may lead to loosening of the prosthesis.[7,36] This is referred to as the stress-shielding effect. If a Ti alloy can avoid this effect, it will cause fewer complications in the body. To solve this, new biomedical Ti alloys focused on beta alloys that are less stiff than alpha alloys and closer to the elasticity of bone at around 50 GPa.[7,37] CoCr is stiffer than Ti with a Young's modulus of elasticity of 200—300 GPa.[12] Lamerain et al[38] did not consider Ti rods relevant in the treatment of deformities because they have a much lower stiffness compared with Ss and CoCr rods.[38]

Nitinol has the advantage of attaining 2 different solid phases based on the temperature of the environment or mechanical stimuli.[14,39] This results in dynamic reversibility of the crystallographic structure of the 2 solid phases.

The parent phase, termed *austenite*, is primarily stable at high temperatures, whereas the secondary phase, termed *martensite*, is stable only at low temperatures and is easily deformable with loading.[14] Therefore when the austenite phase is subjected to cooling or applied stress, it transforms to the martensite phase. Depending on the stimulus that triggers the transformation, the martensite phase