How to Choose between the Implant Materials Steel and Titanium in Orthopedic Trauma Surgery: Part 1 – Mechanical Aspects

Jak zvolit mezi ocelovými a titanovými implantáty v ortopedické traumatologii. Část 1 – mechanické aspekty

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INTRODUCTION

When choosing between metal implants of different materials the surgeon mainly needs to balance the pros and cons of steel and titanium. Economic constraints often do not permit both to be kept in stock and it is necessary to decide beforehand which to choose. The arguments for the use of the “preferred metal” vary. The present paper elucidates the practical aspects based on the complex scientific background that has identified the differences between the two metals in their mechanical, electrochemical, biological and application behavior. The data presented here are intended to help the surgeon when he is confronted with different and often complex clinical situations and problems. The following is an overview of different aspects to help with selection of the proper material for the clinical application. The first part concerns mechanical aspects the second part the biological aspects. Both aspects are discussed with the practical application in mind. Nonmetallic implant materials have seen an increasing interest in the recent past. Plastic materials needed improvement to achieve good strength and avoid creep with loss of e.g. compression and minimizing leakage of chemicals.

The shortcomings of the materials used early on point to aspects that need a solution even today. The first attempts to use implants to maintaining an anatomically correct position of fracture fragments were mostly unsuccessful. Organic materials such as ebony did not offer enough strength to withstand functional loading and/or were not tolerated biologically. Later a variety of metals that were used consisted of a soft grade of iron or steel, which deformed irreversibly when loaded and corroded in body fluids that contain salt at a similar concentration to corrosive sea water. The release of corrosion products mainly Fe, Cr and Ni did not only produce irritation through its toxic components but also had a deleterious effect on local resistance to infection. With the implementation of low carbon, cold worked stainless steel (ISO 5832 1) (5) the strength of the implants was good and it could be shaped to fit the bone surface due to its good ductility. Still, the biological tolerance of steel, though considered "acceptable", left room for improvement in respect to the toxicity of the corrosion product, its allergenicity and what was called "foreign body effect", namely, its poor effect on resistance to infection. This was attributed to a poorly defined "foreign body effect", which expressed the general experience that an infection was sustained until the implant was removed.

In the 1960s the AO group switched to cold worked pure titanium as an implant material that was tolerated without foreign body effect (9). The so called commercially pure (c.p.) titanium (ISO 5832-2) (6) was somewhat less strong than steel but the dimensions of the implants allowed for compensation of the shortcoming. The ductility, a critical measure of tolerance to deformation, as required for shaping the plates, for instance, was less good in c.p. titanium than in steel. A different approach to application was required because there was no prewarning of impending breakage required a different type of application. Surgeons with extensive experience of steel who switched to titanium often experienced screw breakage due to exceeding the torque limit while waiting for the non-existing pre-warning.

To improve strength a titanium alloy ($TiAl_6V_4$) (7) that was used in technical applications was introduced in some countries for trauma surgery. ($TiAl_6V_4$) alloy offers very good strength, but it contains Vanadium. Vanadium is toxic but the extremely low corrosion rate of titanium alloys compensated for the toxic effect of Vanadium as an alloy component. The ($TiAl_6V_4$) alloy was replaced in recent decades by titanium alloys that only contained well tolerated components like Zirconium, Niobium, Tantalum and the like (3). Such materials stood the test of time in applications that were extremely demanding like dental implants where they replaced steel. Therefore, any decision to take advantage of their biological quality for demanding trauma surgery needs to be weighed carefully against the statement "I do not see a difference".

In the recent past plastic materials are considered because of their radiological transparency for instance in distal radius fractures. Fiber reinforced plastics may achieve strength that may live up to the strength of metals but achieve this on the expense of ductility and cost. For the moment we limit the discussion to today's clinical problems namely metallic implants made of steel and titanium with their specific advantages and shortcomings.

MECHANICAL ASPECTS OF STEEL AND TITANIUM AS IMPLANT MATERIAL IN ORTHOPEDIC TRAUMA SURGERY

The "street" opinions regarding the **mechanical** aspects of titanium as a surgical trauma implant material differ widely. Statements of opinion leaders range from "Titanium is brittle and screws do break on application without pre-warning" to "Titanium is somewhat more brittle but without trying to deform the material plastically this is not a disadvantage in practical application". Furthermore, with the introduction of locked plate screws the torque load applied to the screw head is taken up at the screw-head to plate-hole interface which protects the screw thread from large torque and with it from inadvertent breakage. A disadvantage of titanium locked screws consists of the jamming of screws after an extended period of implantation with bone ingrowth, a problem that requires solutions in terms of carefully limiting torque at insertion, choice of surface properties, and design of the components. A new development allows the plate hole to be widened (10) and thus allows the problem of jamming in the "combi-holes" of the Locked Compression Plate to be overcome (11). The following tries to clarify the issue by reference to the research background to clinical problems whereby simplifications must be accepted to enhance understanding of material outside the familiar areas of competence.

In the following, we first address the mechanical characteristics in order to improve general understanding of what can be achieved and what needs to be kept in mind.

Mechanical implant function

In fracture treatment the main function of the implant consists in solidly retaining the reduced position of the fracture fragments. Load tends to displace the fragments and, in turn, the stiffness of the implant resists displacement (Fig. 1). The function of the implant, i.e. regaining painless function, depends primarily on the structural **stiffness** provided to minimize interfragmentary movement. Titanium is ~50% as stiff as steel and so titanium is somewhat more tolerant at application (Fig. 1). The **strength** of the implant, a secondary aspect, limits the amount of load resisted without permanent deformation or breakage. Stiffness and strength of the construct depend on the stiffness and strength of the material and of the more important dimensions (4). Therefore, the slight lack of strength of pure titanium can be offset by increasing some dimensions by only fractions of a millimeter.

Implant material for different applications of implants

Through cold working in steel and alloying in titanium different **combinations of strength versus ductility** can be produced. High strength / low ductility material is used for applications where no deformation is required such as Steinmann pins or Schanz screws of external fixators. The combination of high strength / limited ductility is used for screws and plates while the application as cerclage wire takes advantage of high ductility / limited strength (8). The grades of steel of the ISO material standard (5832-1) (5) reflect these differences (Table 1).

Table 1. ISO standards 5832 Implants for surgery metallic materials

ISO 5832 – 1 wrought stainless steel
ISO 5832 – 2 unalloyed titanium
ISO 5832 – 3 Titan Aluminium Vanadium
ISO 5832 – 14 Ti Mo15Zr5Al3

Lack of pre-warning of impending failure at screw tightening

With respect to the practical application of bone screws, for example, the **ductility**[1] of the implant is a third important and critical factor beside strength and stiffness. A ductile material provides **pre-warning** of impending failure when the torque no longer increases with increasing twist (Fig. 2) (8) – the feeling is that the metal gives way (2). A ductile material like ISO 5832 steel grade 3 allows up to two full turns of twist without increasing torque before breakage. An experienced surgeon feels the change in the relation of twist and torque and limits torque.

If a surgeon with long experience in the application of steel screws switches from ductile steel to more brittle titanium he risks failures due to twisting off the screw head when torque increases while he waits for the non-existent ductile pre-warning of titanium. A surgeon who grew up using only titanium does not expect ductile pre-warning and limits the applied torque. Surgeons who also twist off steel are a minority not considered here.

[1] Ductility is the ability of a material to absorb energy and plastically deform without fracturing (Wikipedia). The term *ductility* is sometimes used here to encompass both types of plasticity, tensile (ductility) and compressive (malleability).

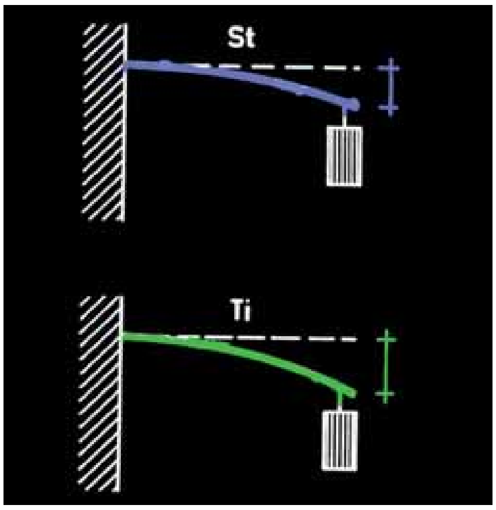

Fig. 1. Stiffness and deflection under load. The same load is applied to both bars. Titanium deflects more than steel.

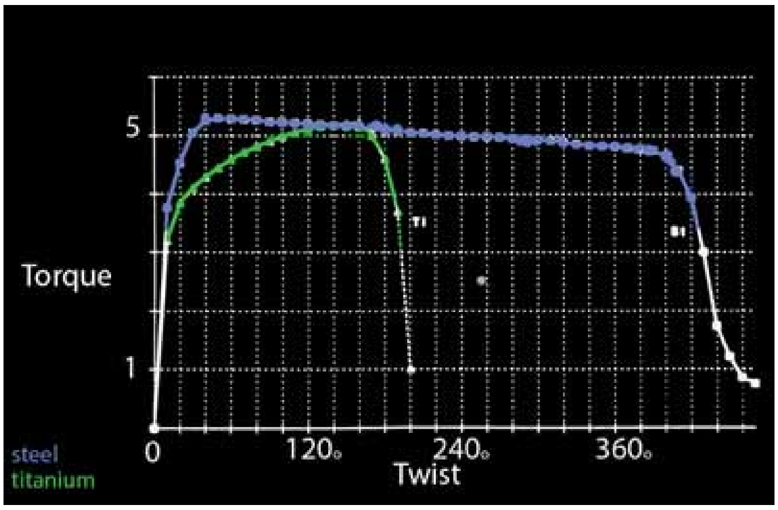

Fig. 2. Pre-warning. Twist / torque plot. Steel screw (blue): Increasing twist is enforced. Torque increases up to a peak value and thereafter the torque does not increase over a wide range of twist before failure occurs. When applying the same twist to a titanium screw (green) after reaching peak torque, failure occurs without pre-warning. Peak torque is similar.

Ductility also plays an important role when, for instance, a plate is deformed to fit the bone surface. Today with locked implants neither of the two aspects of ductility plays a major role: A locked screw is tightened until the screw head is solidly locked within the plate hole, a process which consumes a major part of the applied torque while the screw thread is exposed to minimal torque with minimal risk of thread failure (Fig. 3). These facts require attention, understanding and familiarization.

Should one try to apply maximum torque for best stability of conventional plate screws?

In conventional application of plate screws, i.e. screws which press the plate onto bone, the surgeon often aims at application of maximum torque "for best stability". Trying to apply maximum torque in an attempt to secure maximal stability does not make sense because approaching peak torque goes along with minimizing the amount of additional (functional) load the screw is able to resist.

Jamming of screws at removal

Removing locked titanium screws may be very difficult. Considering locked screws, the characteristic of titanium, namely, "galling" or "micro welding", i.e. when two identical titanium surfaces are compressed they produce very high friction, was considered to be the one and only culprit for jamming. This problem might be resolved by coating one of the partners or by ion-implantation. Still, explaining the large torque required for removal based on "galling or micro welding" did not explain why on the bench jamming was extremely difficult to produce. The observation of Alvarez and A. Fernandez that bone growth into the voids of the interface of the threads (1) and produces a large amount of friction

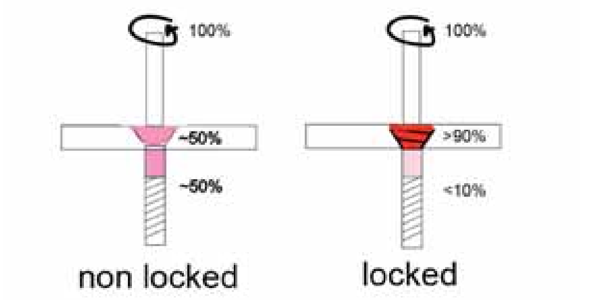

Fig. 3. Torque load of non-locked (LEFT) and locked (RIGHT) screw threads. At insertion about 50% of the torque applied to non-locked screws is exerted onto the screw thread. Torque applied to locked screws is used up at the screw to plate interface and the screw thread below is protected.

Fig. 4. Jamming of screws at removal. Plate hole (L) and screw head (R). Titanium friction may contribute to difficult removal but as this picture from Alvarez and Fernandez show bone ingrowth is the real culprit. Root and flanks of the thread interface are covered with sticky bone. Only the crest of the thread is confined to metal to metal contact (1).

Fig. 5. Deformation of PLATE: When shaping a plate to fit the bone surface sharp and repeated bends need to be avoided.

ABOVE: Here smooth bending is supported by the continuous stiffness of the implant.

BELOW: discontinuous stiffness of the plate results in areas of sharper bending.

offers an explanation that may allow an unacceptable problem to be resolved. Preventing ingrowth or minimizing adherence of bone to the flanks of the thread needs to be studied (Fig. 4). Furthermore, the fact that between the end of the thread and the undersurface of the screw head a segment of the screw with a smaller diameter must be overcome at removal requires an appreciable amount of torque. The latter torque together with bone ingrowth and with thread friction may result in a very demanding and unacceptable surgical procedures. Each of these elements needs attention.

The tolerance of implants to shaping

When an implant, such as a plate, is adapted to the bone surface, as is usually done in non-locked conventional application, a question arises regarding the **effect of deformation on the remaining strength** of the implant. When small local deformation is applied either by single small bending or twist and/or by spreading the deformation over a large distance like in the helical plate (10), the effect of the deformation may be understood as cold working, which may even increase strength. Repeated and/or large deformations producing large local strain will diminish strength (Fig. 5). This applies to both steel and titanium.

CONCLUSIONS

Steel and titanium as implant materials in trauma surgery provide similar strength but behave differently in respect to ductility. As ductility is closely related to pre-warning of impending breakage a surgeon switching from ductile and with it pre-warning steel to titanium needs to understand and act accordingly to avoid unexpected failure. This has led to basic criticism regarding the "strength" of titanium, a criticism that addresses the surgeon more than the material. Taking advantage of the superior biological properties of titanium requires understanding and acting accordingly. The widespread intention to tighten plate screws as much as possible for "better stability" is questioned. An observation, that may explain jamming of locked plate screws at removal, namely increased friction due to bone ingrowth, requires full attention to prevent the unacceptable jamming.

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