THE USE OF CERAMIC COATINGS IN ORTHOPAEDIC IMPLANTS

Titanium Nitride Ceramic Coating Articulating against Polyethylene and Cartilage

Introduction:

Joint replacement arthroplasty is considered to be one of the most successful surgical procedures.
Until recently joint replacements have only been carried out on older, less active patients.
The success of these joint replacements has encouraged the use of artificial joints in younger persons with a more active lifestyle.(1,2,3). The life expectancy of this younger patient is higher than the lifespan of the average knee or hip implant.(5). The revision rates in total knee replacements is considerable higher in younger patients.(4)
The most commonly used orthopaedic implants are of the metal-on-polyethylene type. Polyethylene wear particle induced osteolysis has been identified as the main cause of failure of total knee arthroplasty and in particular the occurrence of fatigue-type wear that can destroy a tibial inlay in less than 10 years is a major concern.(6,7,8).

Parameters Influencing Wear in TKA

There are numerous parameters influencing the wear of polyethylene components in total knee arthroplasty: the patient's life style, the level and type of stresses on the articulating surfaces, material properties,
imperfections of polyethylene components, and the coefficient of friction.(9).

Improving Implant Design Geometry:

In a knee implant the stress level depends on the load and the contact area between the articulating tibial and femoral components. The contact stresses in many non-mobile bearing knee designs are much higher than previously estimated and can easily exceed the yield point of UHMWPE (Ultra High Molecular Weight) by as much as 3 times.(10).

The **Introduction of Mobile Bearings** into the knee designs by Goodfellow and O'Connor and the further improvement of the meniscal bearing design by Buechel and Pappas has lead to the view that three compartmental knee implant design can contribute substantially towards the reduction of polyethylene wear.(11,12,13,14).

Contact Area

In the mobile knee designs currently available great differences can be found in the surface contact area between the femoral implant and the polyethylene articulating counter surface.(15,16).
The ACS knee has its highest surface contact area at extension (where the highest load occurs) and at 60^{o} of flexion.

Age and activity after TKA

patient Age	average steps /year
< 60 years	1 200 000
> 60 years	800 000

Failure rate and ages in TKA

age (years)	percentage of failures
< 65	12 %
65 - 75	10 %
> 75	4 %

Life expectancy (females)

age	expected to live another
50 years	34 years
67 years	20 years

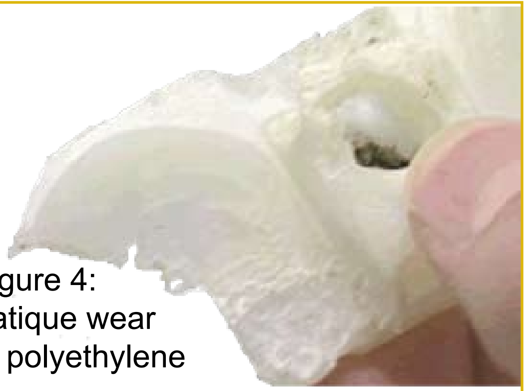

Figure 4:
Fatique wear
of polyethylene

Fig. 5: The ACS® knee implant with mobile bearing.

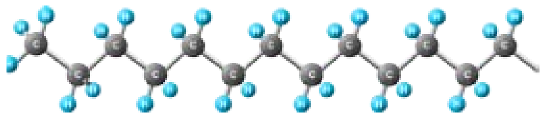

Fig. 6: Polyethylene molecule

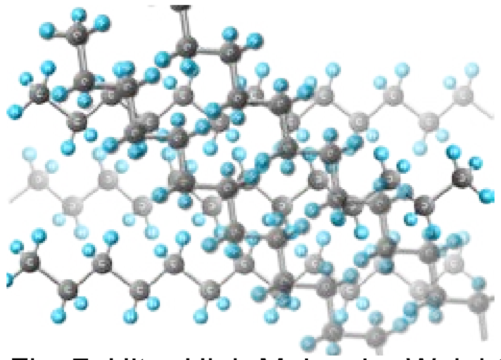

Fig. 7: Ultra High Molecular Weight Polyethylene (UHMWPE)

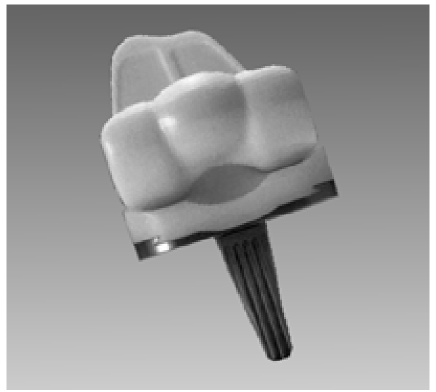

Fig. 8: Block ceramic femur component

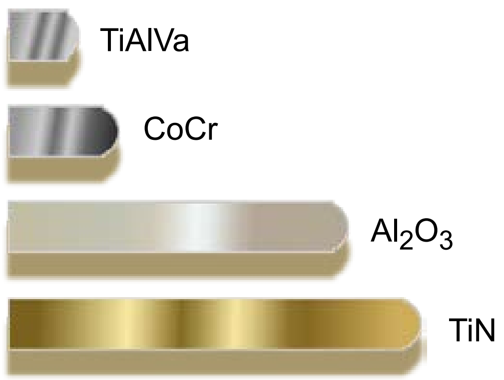

Fig. 9: Relative hardnesses in Vickers of orthopaedic implant materials

The polyethylene

Many attempts have been made in the past to improve the wear characteristics of polyethylene, including carbon-fiber reinforcement (PolyTwo^{TM}) ,polymer reprocessing like Hot Isostatic Pressing (Hylamer^{TM}).
Hot Pressing (PCA^{TM}) was another attempt to improve the articular surface but was associated with early delamination. History has shown that the in vitro investigations may not fully predict the performance in vivo.(17).

Cross linked polyethylene ?

Laboratory simulation demonstrated that wear resistance of polyethylene improves with increased cross linking of the polymer chains. However it may also change the amorphous or the crystalline regions of the resulting polymers, or both, potentially affecting mechanical properties and fatigue characteristics. Cross Linked PE may work well in hip designs, the application in knee replacement is still under debate.(18,19).
In the ACS® knee standard ram-extruded GUR 1000 Polyethylene (stearate free and Ethylene Oxide sterilized) is used.

Metal Substrate: Damage or scratching of the metal counterface has been shown in hips and knees to accelerate polyethylene wear. In the hip the use of ceramic femoral heads (Alumina^{TM}, Zirconia^{TM}) is recommended. They are more damage- and scratch resistant and show extreme lower long term wear rates.(20).

Monolithic Ceramic components have not shown to reproduce the same clinical longivety as the Cobalt Chromium implants yet.(21).

Oxidized Zirconium implants show excellent wear characteristics against polyethylene, but at this time require the use of bone cement for fixation.(22,23).

Ceramic Coatings demonstrate the following advantages :

- increased hardness of the articulating surface (fig. 9)
- increased scratch resistance
- lower friction coefficient
- improved wettability
- reduced wear of the counterface
- higher corrosion resistance
- decreased metal ion release
- enhanced bone ingrowth capacity
- increase fatique strength
- increased biocompatibility

Titanium Nitride Coating

In the late 70 and 80's of the last century some of the Cobalt Chromium implants had a small Nickel content to add to strength of the implant. Nickel is the primary cause for metal sensitivity, although some patients have shown to be hyper-sensitive to other metals including Cobalt and Chromium.

Since the end of the 1990's TiN (Titanium Nitride coatings) have been successfully applied to shield the body from metal ions that could cause allergic reactions.(24,25).

Fig. 9: Lymphadenitis in a patient with Ni-hypersensitivity after TKA.

Less Abrasive Wear from Carbides

During the casting of orthopaedic components the carbon content of the alloy will form carbides, compounds of metal and carbon. Where these much harder particles protrude beyond the surface they may harm the articulating counter-face. By covering these carbides with a harder ceramic this wear will be reduced.(26,27).

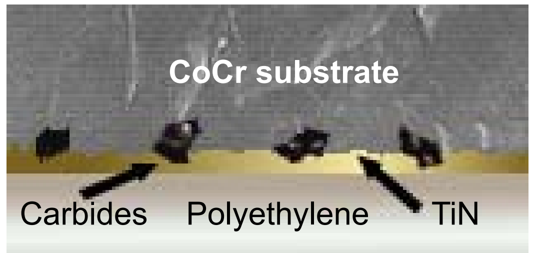

Fig. 10: TiN covering carbides

Higher resistance to scratch formation :

Wear simulator tests are usually done with *new* implants. However it is known that particles in the body such as bone chips and bone cement particles can lead to third body wear.(26)
Ceramic coated implants have a higher resistance to this scratching.(28,29).

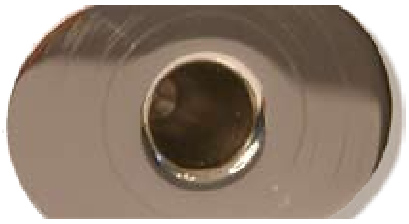

Fig. 11: Scratched non-coated CoCr tibial component

Less deeper Scratches.

The height of the lip of a scratch is directly related to the amount of abrasive wear. TiN coated implant have a lower scratch lip than non-coated prostheses.(30).

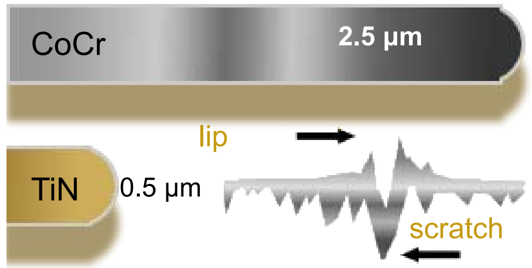

Fig. 12: Height of lip of scratches

Less wear from scratched components

When a wear simulator test is performed with explanted components is shows the reduction of abrasive wear in TiN coated implants. (27).

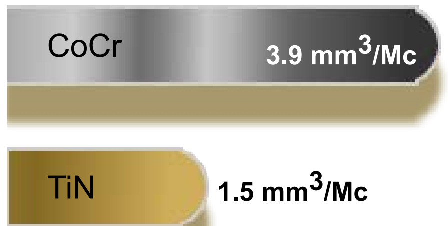

Fig. 15: Wear rates of scratched components in mm^3/million cycles

Lower Coefficient of Friction

Wear damage to the articulating surfaces is associated with the frictional forces at the interface. The coefficient of friction depends on the materials, the surface finish of the articulat-ing surfaces and the lubricating regimen.(31).

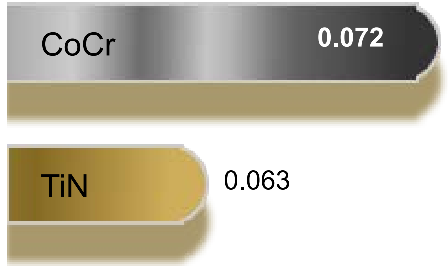

Fig. 16: Coefficent of friction

Better Wettability

When placing a droplet of de-ionised water on the surface of an implant, the contact angles can be measured. TiN shows to be more hydrophilic than non coated CrCoMo. A better wettability will increase the lubrication, decreasing the coefficient of friction and thus will aid to reducing the wear. (29,31).

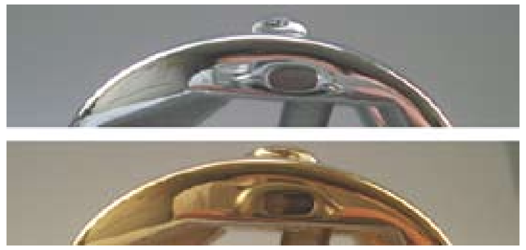

Fig. 17: Wettability of non coated and coated femoral components.

Lower Surface Tension:

DOT Rostock established the relation between wettability angle and surface tension of non-coated and TiN coated implants.TiN coated implants show a reduced surface tension. (32).

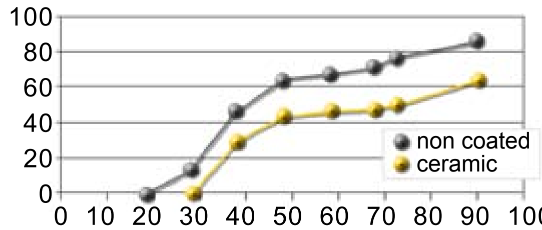

Fig. 18: Relation between surface tension (in mN/m) and wettability angle

Better and faster bone in-growth.

This patient received a Titanium Nitride coated knee implant, but unfortunately she fell 3 months post-operatively. She tore both collateral ligaments and the implant had to be revised. There is abundant bone in-growth on both components. (Pictures courtesy of Mr D. Woodnutt, Consulting Orthopaedic Surgeon Morriston Hospital Swansea UK)

Fig. 19: Bone ingrowth in TiN coated CoCr knee replacement components.

Less Ion Release

All implants corrode at a rate determined by their surface area and this causes the release of metal ions, Fig. 20 which was derived from a test done at the University of Würzburg, Germany shows that the passive Chromium ion release (without articulation) is less than 10% of a non-coated implant after10 days in NaCl saline solution at 100^0C.(35).

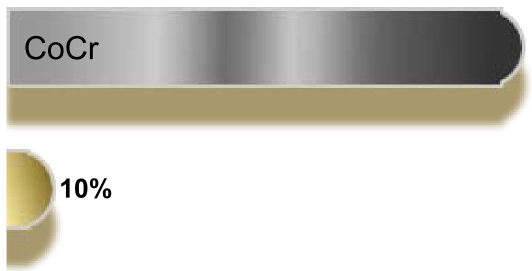

Fig. 20: Chromium ion release

Quality Assurance

The application of the Titanium Nitride Ceramic coating is by Physical Vapour Deposition.(*) The name PVD stands for a wide range of applications each with its own physical characteristics. In order for the coating of an implant to be able to function long term it is crucial that the PVD process is reliable, reproducable and has proven itself in clinical application.
The adhesive strength of the coating onto the substrate is of vital importance. Various in-process and batch quality checks are performed.

Fig. 21: TiN coated components

Rockwell test

A diamond cone penetrates the coating layer with defined force. This deforms both the coating and the substrate. An optimal coating will show no delamination (fig 22 left). Insufficient adherence of the coating will result in delamination as seen on the right in fig 22. (31,34).

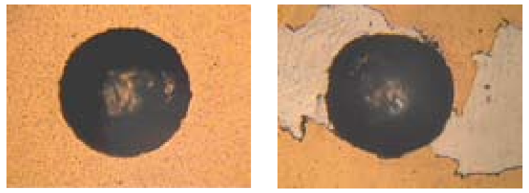

Fig. 22: Two PVD coated implants with different adhesive strengths

Bending test

A metal strip is included with each batch of implants to be coated. To check the adhesive strength of the coating the strip is bent up to 180°. A uniform crack network is seen without delamination proving optimal adherence.(34).

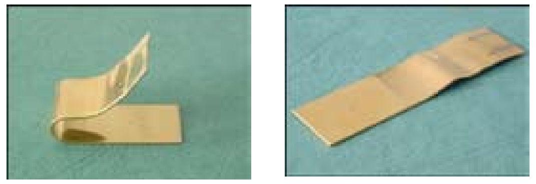

Fig. 24: Bending test to prove adhesive strengths

Technical Data of TiN

Coating Thickness 4.5 +/- 1.5 µm
Hardness TiN : 23000 (+/- 2000 MPa)
Hardness CrCo : 5000 MPa
Adhesion Strength HF 1-4
Surface Roughness : Ra < 0.03 µm

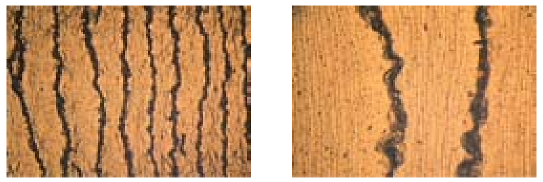

Fig. 25: After bending test
magnification 100x magnification 400x

Pin-on-Disk test

A documented cause of scratches in implant components is the presence of bone cement particles. A disk of PMMA bone cement is used against a TiN coated metal disk. No delamination is seen. not even at a load of 500 MPa , which is 50 times higher than the normal in vivo pressure in the knee (< 10MPa).(26, 31,34).

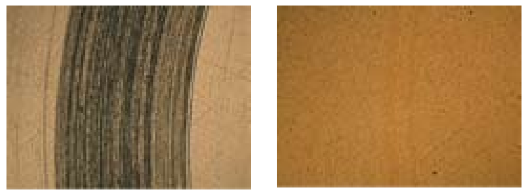

Fig. 23: Pin-on-Disk test of PMMA on TiN coated substrate.

(*) DOT GmbH
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Germany

A selection of implants available with TiN Coating

ACS® Mobile Bearing Knee Prosthesis. Available in cemented and cementless design. posterior stabilized, revision and tumor system

ACS® Femora for Cementless Fixation with or without HA/TCP

ACS® Cemented Tibia with shaft extensions

ACS® Posterior Stabilized Femoral component and detail of the mechanism.

28 and 32 mm Titanium heads for Hip Implants articulating against polyethylene

Capica® Shoulder Surface Replacement

ACS® Semi Constrained Mobile Bearing Knee Prosthesis.

Virtually any orthopaedic implant articulating against polyethylene may benefit from the application of a ceramic surface coating.

ACCIS® Total Hip and Resurfacing Hip Replacement

ACCIS

Advanced Ceramic Coated Implant System

A special application of ceramic coating on orthopaedic implants is the ACCIS® coating in which a Ceramic Coated surface articulates against a Ceramic Coated Surface. It is available forTotal Hip and Resurfacing Hip arthroplasty. A dedicated brochure is available.

Agilon® shoulder and Mutars humerus replacement

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