Hemocompatible TiN coatings

# Designing a New Heart




**Roman Kustosz, M. Sc., works on the implantable artificial heart**

**Roman Major, M.Sc., works on the advanced medical materials**

**Professor Tadeusz Wierzchoń investigates new materials' structures**

**Professor Bogusław Major develops coatings for the artificial heart**

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**Artificial heart implantation in an animal experiment**

**Artificial heart prostheses are a well-accepted method of end-stage heart failure treatment. Interdisciplinary work on constructing new internal prostheses highlights modern medicine's extensive dependence on materials science**


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The POLTAH artificial heart

Heart disease is still one of the most important public health epidemics at the outset of the 21st century. Heart failure is a critical consequence of this illness, exerting an ever greater impact on the population. According to recent data, 0.4%-2% of all Europeans suffer from heart failure. Since a decreasing number of organs are now being donated, freezing the number of heart transplantations at 3100-3200 cases a year worldwide, mechanical heart prostheses have been recognized as an available temporary heart substitute.

## POLCAS – the Polish Cardiac Assist System

The development of cardiac prostheses has been underway in Poland for almost 20 years now. The list of cardiac assist achievements made by the research program being carried out at the Artificial Heart Laboratory of the Cardiac Surgery Development Foundation in Zabrze includes:

- POLVAD, an extracorporeal pneumatic ventricle assist device, implanted in over 140 cases since 1996, with the longest support duration of 94 days,
- a pneumatic total artificial heart, which was clinically implanted (experimentally) in 1998,
- a pneumatic driving unit for ventricle assist devices (VAD) and total artificial hearts (TAH), in clinical use in over 70 cases since 2000.

This system has been used as a "bridging" treatment to both heart recovery (the longest successful support - 53 days) and to heart transplantation (43 days). Further progress in terms of support duration, longevity, and treatment comfort, however, demands that an implantable system be developed. Our most recent project aims to develop the following:

- a partially implantable pneumatic VAD,
- a totally implantable hydraulic VAD,
- a totally implantable artificial heart.

One crucial issue that must be addressed before developing such devices concerns what kind of materials they should be built of.

## Hemocompatible materials

Blood-contacting materials are routinely used in modern medicine. When blood comes into contact with something foreign, such as biomaterial, the first clinically manifested process that occurs is the activation of hemostasis (clotting). The first step of hemostasis involves the adsorption of blood proteins, followed by platelet adhesion and activation. A variety of agents, such as collagen, plasma proteins and the products of platelet metabolism, can cause this activation of platelets. The process is influenced by the fluid mechanical properties of blood flow. A key issue in this context is the wall shear stress, meaning the force exerted by the flow per unit of wall surface area.

The materials used in blood-contacting devices have often been chosen based on their physical characteristics, such as flexibility or rigidity, mechanical strength, transparency, degradability, etc. Thus, optimal thrombogenicity (the tendency to encourage blood clotting) may not always be achieved. Furthermore, increasing evidence is now being reported that the thrombogenic properties of a medical device during clinical use are different from those observed during *in vitro* testing under static conditions. The response of the hemostatic system may differ for each application, depending on the flow conditions.

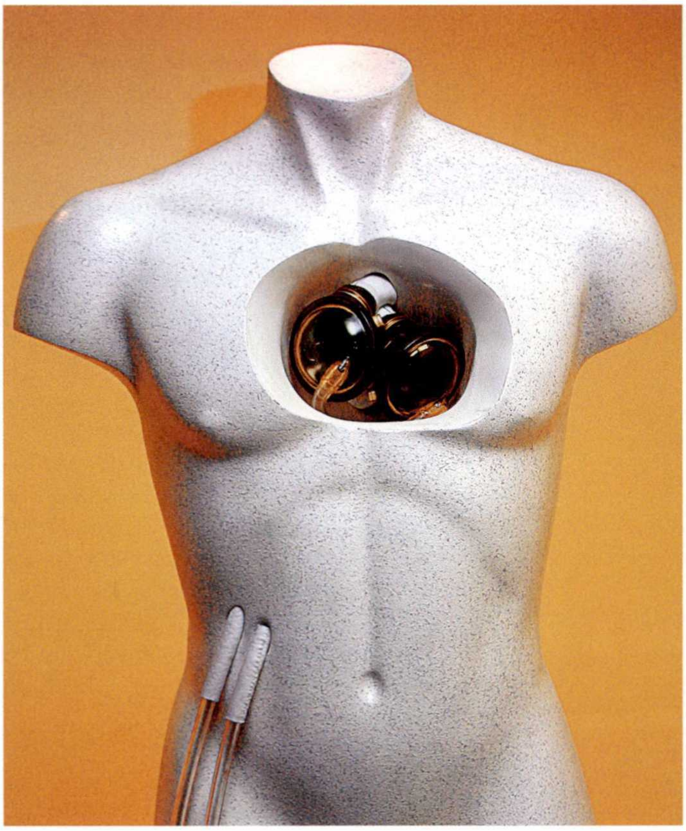
One of the biomaterials being considered for use in constructing an internal ventrical device is titanium. This element is normally present in human tissue at concentrations of 0.2 parts per million. No clinical tissular toxicity has been observed, even at local concentrations higher than 2000 ppm. Titanium has been shown to be biologically inert, and it does not induce either toxic or inflammatory reactions in connective or epithelial tissues. Titanium is bacteriostatic (inhibitive to bacteria) and it is neither significantly conducive nor significantly inhibitive to different enzyme systems specific to toxic reactions. Titanium and its alloys do behave poorly under friction, since titanium particles have often been detected in the tissues and organs of organisms with titanium implants. But titanium's real biological actions, if any, have not yet been established. The low wear resistance of titanium and its sometimes-mentioned inflammatory reactions led us to look for methods which could improve this material's properties for medical applications.

Well-known titanium nitride (TiN) coatings have proven effective in making cutting tools more durable. TiN is now being eyed as a perspective biomaterial. As a blood-contacting material, titanium nitride has to undergo more than the typical biocompatibility tests. It also has to meet the hemocompatibility criterion in both *in vivo* or *in vitro* tests.

## TiN coatings via pulsed laser deposition

In search of a suitable biomaterial for ventricular assist device application, TiN coatings were chosen as a blood contacting material. Thin coatings of TiN can be deposited by a number of physical and chemical vapor deposition methods, including evaporation, ion plating and sputtering. In many cases, however, the substrate cannot withstand the elevated temperature these methods entail. Thus there is great demand for developing low-temperature deposition processes, such as pulsed laser deposition (PLD), a technique that is now being cooperatively developed by the Institute of Metallurgy and Materials Science in Kraków and the Institute of Optoelectonics at the Military University of Technology in Warszawa.

In the PLD technique, a pulsed laser beam is focused onto a target in order to evaporate its surface layers in ablation mode, under vacuum or low-pressure process gas conditions. The vaporized material, consisting of atoms, ions and atomic clusters, is then deposited onto the substrate. The outstanding advantage of this technique is its ability to deposit thin films of very high chemical purity and adhesion onto various substrate materials at room temperature. Furthermore, a high rate of film growth can also be achieved on surface areas situated perpendicular to the target's surface plane by using a low pressure process gas. Applying a reactive process gases also makes it possible to vary the film stoichiometry over a wide range.



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**Ilustration of a POLTAH pneumatic artificial heart when implanted**

## Film deposition

High-purity titanium targets were used in ablation experiments carried out by means of a pulsed Nd: YAG laser system, which provides four beams of 1064 nm wavelength, 0.6 J pulse energy and 10 ns pulse duration at a repetition rate of 50 Hz. The thickness of the TiN films deposited on a polyurethane or metallic titanium sheet substrate, given a constant level of nitrogen flow and constant laser deposition parameters, was related to the number of laser shots. Measurements of the residual stresses present in TiN deposited on metallic titanium revealed that their values are influenced by the roughness of the substrate surface. The residual stress value measured in the TiN deposited layer was highest when the layer itself was thinnest, i. e. 0.5 μm. This suggests that the mechanism of growth in the initial stage differs with respect to that subsequently observed, when the layer thickness increases.

We surmise that the kinetic processes associated with the formation of polycrystalline or columnar morphology contribute to the strain field in the deposited layer. Crystallographic texture analysis performed for the metallic substrates of different roughness show a correlation between the substrate and the layer. A cross-section analysis of samples with polyurethane substrate using scanning electron microscopy (SEM) revealed the anchoring character of the deposited layer, which proves that there is high adhesion. A line scan of the Ti element content revealed the continuous action of the element to the substrate. Similar results were obtained for layers 1.0 and 3.0 μm thick. Atomic force microscopy (AFM) analysis was carried out to examine the surface morphology of the layer deposited on the polyurethane substrate.

Transmission electron microscope (TEM) observations were performed for a TiN layer deposited on a pure Ti substrate. The ring shape of the electron diffraction pattern proves that the deposited layer is of a nanostructural nature. The blurred character of the interphase between the TiN deposited film and the metallic substrates suggests that there is good film adhesion.

## Concluding remarks

Artificial heart substitutes have now become a very important medical tool. They need to be as low-invasive as possible in order to maximally extend patients' waiting time for transplantation. Unfortunately, external ventricle assist devices entail too many contacts between the internal and external human environment, which could lead to inflammatory reactions. Our research has focused on two materials that could potentially be applicable for devices to be used within the heart chamber itself: polyurethane (PU) covered with hemocompatible titanium nitride (TiN), and pure titanium with a TiN coating. The pilot results of material microstructure studies show that pulsed laser deposition can be used to produce such TiN coatings at room temperature, making it possible to fabricate fine grained and uniform layers, suitable for use in internal heart devices. This research is thus an excellent example of a project where medical science and materials science are working hand in hand.

## Acknowledgment

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**Further reading:**

Religa Z., Czaplicki J., et al. (1992). Przeszczep serca zwierzęcego człowiekowi, *Polski Przegląd Chirurgiczny, 64*, 3 243-251

Czarnowska E., Wierzchoń T., Maranda-Niedbała A., Karczmarewicz E. (2000). *J of Mat. Sci.: Materials in Medicine 11*, 73

Major B. (2002). *Ablacja i osadzanie laserem impulsowym*, Kraków: Wydawnictwo Naukowe Akapit

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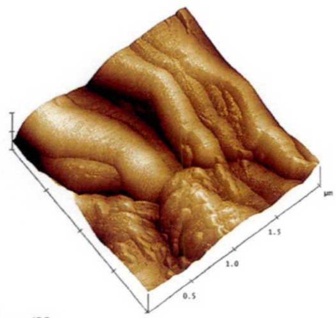
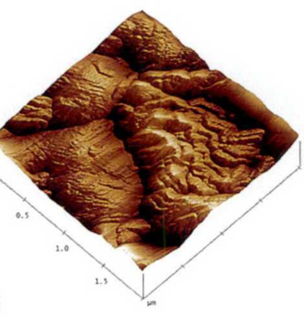


0,5 μm



1 μm

**Microscopic image of the artificial heart coating**