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Analysis of biomedical materials and parts: advanced nano(micro)-characterization by neutron beam techniques

ABSTRACT

The progress of the study of biomedical materials and devices, as well as their advancement, especially depend on the application of efficient characterization techniques to evaluate key physical parameters connected to performances, damage and quality. A main aim is to establish correct relationships between macroscopic functional properties and nano(micro)-characteristics. Numerous invasive biomedical devices, e.g., as planned to remain in the human body for the entire life of the patient, once implanted, operate in the ionic environment of the blood and in contact with the released substances and cells. The consequent effects must be added to the other aging factors: the dynamic stress of the pulsation is one of these effects and concerns the operational of self-expandable stents installed in arteries such as the carotid to correct stenosis. Neutron beam techniques are an excellent tool to study materials and parts of biomedical interest, contributing to solve important questions linked with the methodological restrictions of the analysis methods generally adopted: their results, complementarily, can help improving quality and functionality. This paper concerns the advanced nano(micro)-characterization of biomedical materials and parts by these non-destructive and non-invasive nuclear methods. Some examples related to the biological field are also mentioned. For applications in the biomedical and in the industrial sectors, the Rogante Engineering Office has developed particular methodological approaches and dedicated processing and treatment procedures.

***Keywords**: biomaterials, biomedical devices, neutron beam techniques, nanostructure, microstructure.*

1. INTRODUCTION

Scientific advancement has recently contributed unique information on the molecular bases of illnesses, allowing to find new targets for drug discovery. Since the limitations of drug research and development, however, only in a reduced part of cases this knowledge has been converted into new therapies: just ~10% of compounds entering phase 1 clinical development are actually reaching the subsequent stage, the failure rate in phases 2 and 3 being ~50%, especially due to lack of efficacy. It is necessary, thus, to screen selected molecules in short time, to decrease the timing on drug discovery [1]. A key issue in biology is to know how atoms and molecules organize themselves and move to achieve a biological function [2]. Structural biology currently exploits various techniques - mainly, cryo-electron microscopy, nuclear magnetic resonance spectroscopy and X-ray crystallography -, e.g. for the structural analysis of proteins, polynucleotides, carbohydrates, lipids and other bio-macromolecules. However, complementarily, neutron beam techniques (NBT) can contribute in essential way to answer definite relevant questions of biology, for instance regarding structure and dynamics of lipid membranes, colloids for drug delivery or proteins.

Concerning biomedical devices, several of them, once implanted completely or partly in the human body by surgical or medical intervention, are planned to stay there for the full patient's life: thereby being exposed to all the insults caused by the biological environment, such as the blood's ionic environment, the secreted cells and other substances, together with additional aging factors. Self-expandable stent, e.g., installed in arteries

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such as the carotid to correct a stenosis, are also subjected to dynamic stress of the pulsation (hundreds of million of loading cycles, with further single-event overloads). The prosthetic heart valves, stents and other devices installed intravascularly, each with characteristics of resistance (especially, metal ones), are submitted to a continuous development in the diagnosis of the materials involved [3]. Oesophageal stents, once implanted and expanded, can experience late fractures most probable due to corrosion. Minor fracture can occur, thus, without consequences to the stent's longevity, or arriving to complete failure, with consequent severe harm to the patients. Fracture occurrences of up to 50%, indeed, possibly due to in vivo cyclic displacements, have been reported in some stents after one year [4]. Stent fractures are often a hidden complication of femoro-popliteal stenting that can be associated with important disease. Some other examples of stent failure can be reported as follows: a complete double fracture of a Nitinol stent [5]; a stent twisting along the major axis, with complete loss of structural integrity and with occlusion of the popliteal artery a few millimetres above the stent fracture and some collateralization, documented by the antero-posterior projection of a diagnostic angiogram [6]; an overload fracture of a stent [7].

The progress of such devices directly depends on the application of effective methods of characterization, to assess their damage by aging, in order to establish the correct relationship between the characteristics of defects and functional macroscopic properties. Analyses of microstructure and fracture surfaces indicate that uncommon aspects of Nitinol fatigue behaviour are linked with domains of high dislocation densities, internal stresses, stabilized martensite and micro-fissures [8]. Fatigue tests can be carried out, e.g., collecting Nitinol samples and fatigue data with reference to replicated oversizing settings and pulsation cycles, evaluating fatigue safety factors to estimate fatigue resistance.

Other constitutive materials of biomedical devices are, e.g., medical-grade thermoplastic polymers and, in particular, polyester, polyether and polycarbonate materials, which are among the key polymers used in vascular catheter and central venous catheter applications.

Also in these cases, NBT can give an important support, supplying complementary information to solve key questions.

2. ADVANCED NANO(MICRO)-CHARACTERIZATION BY NBT

Neutron methods are an essential and unique part of the science tool kit to exploit information about matter's properties and behaviour at the atomic and molecular levels. This is essential to design novel devices, drugs and other materials, solving intricate problems. Intense neutron beams are created in nuclear reactors or accelerator based neutron sources. Neutrons are able to probe matter's structure and dynamics in the range from meso- to nano-scale and from seconds to nano-seconds [9]. They can provide in a non-destructive way significant insights, e.g., into the behaviour of viruses, helping to search effective diagnostics and therapies. The expertise in neutron structural biology, biophysics, chemistry and nanoscale materials science and engineering can aid developing physico-chemical and environmental controls to virus infection, replication and transmission, as well as new diagnostics and therapeutics of diseases [1].

The NBT adoptable to characterize biomedical materials and parts comprise small angle neutron scattering (SANS), neutron reflectometry (NR), neutron diffraction (ND), neutron imaging, neutron crystallography (NC) and neutron spectroscopy. SANS, exploiting cold neutrons produced by middle or high flux reactors, allows characterising materials at the nano(micro)-scale and is able to provide very precise measurements of structural parameters of the systems with nano(micro)-particles, supplying statistical information averaged over a macroscopic volume. Parameters reflecting the structural features of nano(micro)-scale inhomogeneities such as concentration, size, volume fraction and interface area, furthermore connected with ageing processes [10], can be monitored by measuring the neutrons' scattering from the investigated samples in angles smaller than 5 degrees. The low angle part of the SANS scattering curves ($qR<1$) contains information about the overall sizes of the scattering objects; the medium angle region characterizes the particle shape, and at larger scattering vectors interface features can be deduced. The scattering vector q is defined by the neutrons' wavelength and the scattering angle, while R is the size of the scattering particle. The scattering intensity curves are modelled by proper mathematical functions. For theoretical bases of the SANS technique, please refer to [9, 11-13].

For most structural biology experiments, SANS focuses on measuring the elastic (i.e. without energy transfer) and coherent (i.e. direction-dependent) scattering of neutrons from the atomic nuclei of the biological isotopes found in proteins, polynucleotides, carbohydrates, lipids, etc. [14].

In studying the function of assembled viruses and of other large biological complexes, SANS allows:

- distinguishing specific regions (RNA, lipids and proteins) of the virus, by adopting advanced deuteration methods
- mapping out the arrangement of the various components, thereby contributing to structural studies
- supplying a larger picture of full molecular complexes at lower resolution, compared to the atomic-resolution structure of small biological assemblies as provided by using cryo-electron microscopy and nuclear magnetic resonance.

The possible advantages in using NBT as innovative approaches of advanced characterization of viruses are described in [1].

Combined with macromolecular deuteration and solvent contrast variation (H_2O/D_2O exchange), moreover, SANS allows focussing selectively on the signal of definite proteins in multi-protein complexes or in blends of isolated proteins [15].

NR, as surface technique enabling to measure non-destructively thickness and chemical composition of one or more thin layers at a surface or an interface, is especially useful in the fields of biophysics and soft matter. It can probe, e.g., thin films at buried interfaces or enclosed in bulky sample environment equipment. Biomolecular deuteration allows modern labelling approaches to highlight specific structural features and to resolve with improved correctness the location of chemically similar molecules within a biological thin film. Lipid membranes are one of the most significant subjects in biology, since their implications in several aspects of human life; on the other hand, thin films are more and more studied in the context of novel biomaterials, hence the adoption of natural biomolecules is playing a increasingly important role. Applications of NR for structural characterization of biological samples, such as lipid membranes, protein films and protein-lipid interactions, are described e.g., in [16].

NC can supply crucial information related to the structural analysis of biological molecules, e.g., concerning: proteases or virus spike proteins, responsible for mediating the attachment and entry into human cells that it affects; the precise coupling mechanism of virus and the receptor proteins of the cell membrane. This technique allows also determining the positions of H atoms in molecular structures: highly polarized H atoms or protons (H+), actually, cannot be observed by X-rays, since they have no electrons.

Massive Nitinol samples - one untreated, other two submitted to powder immersion reaction assisted coating (PIRAC) at different temperatures and times, then water quenched and differently coated - were tested:

- by SANS, using a double-bent crystals instrument, to determine the structural features of various defects (i.e., precipitates, voids, dislocation groups and borders of crystallites) as dependent on thermal treatment
- by high-resolution ND, using a high resolution three axis neutron optic diffractometer, evaluating the macro-strain components resulting from angular shifts of diffraction peaks and the micro-strains in the plastically deformation region by means of profile-broadening analysis.

As results, the PIRAC treatments presented an influence on the Nitinol quality, progressively generating the defects detected in the incoherent scattering and slightly affecting the base properties of the bulk material [17].

Commercial Nitinol stent were tested by SANS. As results, the structure of these stents at the scales R ~ 1-30 nm can be considered as composed of tiny particles (size ~11 nm) associated into more extended structures (size ~24 nm) and they exhibit contacts at the distances comparably with their diameter [17-19].

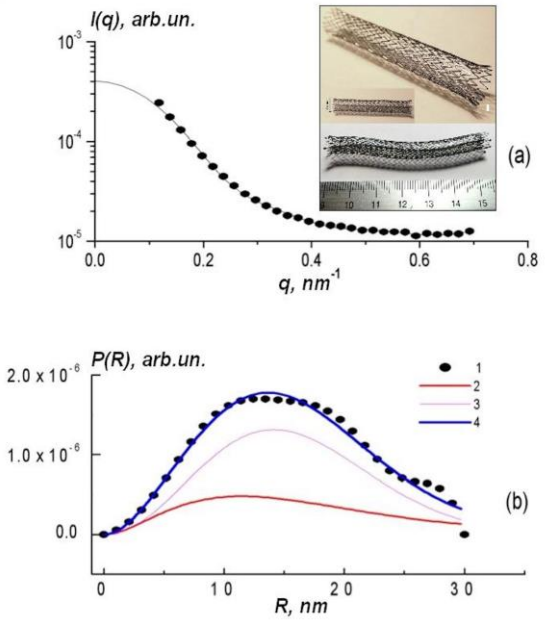

Figure 1. SANS analysis of Commercial Nitinol stents. SANS-intensity I(q) (a) and distribution function P(R) (b)

Slika 1. SANS analiza komercijalnih Nitinol stentova. SANS-intenzitet I(k) (a) i funkcija raspodele P(R) (b)

Figure 1 shows the investigated stents, the scattering function line (a) and the related data *P(R)* (b, data 1), the partial (2, 3) and total (4) correlation functions [17]. In particular, the curve *I(q)* has been used to obtain the distributions of the

distances *P(R)* between the scattering centres (defects in material), of which the ensemble gives the resulting data.

The materials used to produce mechanical heart valves include the cobalt-chromium or stellite alloy (constituting the cage), the cobalt-chromium-molybdenum alloy, the Ti6Al4V alloy, polyethylene terephthalate, polytetrafluoroethylene or Teflon (constituents of the valve ring) and pyrolytic carbon or pyro-carbon (constituent of the occluder). Among the complications related to mechanical heart valve prostheses, there are structural deterioration and breakage or blockage of the mobile element, due to fatigue and tension phenomena. Also in this case, an in-depth analysis using NBT allows obtaining complementary results to the classic analyses, providing useful data on key parameters and information to improve existing materials and devices and possibly devise innovative components, increasing performance and enhancing the levels of functionality, quality and safety [20]. An advanced nano(micro)-scale characterization of Co25Cr5Mo5W and Ti6Al4V biomedical alloys produced by laser powder bed fusion (LPBF) was performed by adopting NBT, complementarily to scanning (SEM) and transmission (TEM) electron microscopy and X-ray diffraction (XRD), to achieve additional key information on the structural features responsible of material performances [21]. Concerning the Co25Cr5Mo5W alloy, the SANS analysis confirmed the presence and the evolution of precipitates from the as produced (AP) sample and that after thermal treatment (TT), showing the presence of clusters in both samples. The stronger scattering appearing after the TT testified mainly a growth of the precipitates size. In close agreement with the results from SEM and TEM used to observe shape, size and density of nano(micro)-defects, SANS evidenced higher density of precipitates, increased in size with well-defined borders after the thermal treatment.

These precipitates obstacle the dislocation motion, with consequent lower ductility and increased hardness in the sample after TT. Concerning the Ti6Al4V alloy, a ND analysis was carried out on the raw powder as well as on the AP sample and that after TT. The ND results, in addition to confirm the fully α-Ti structure of the raw powder already observed by XRD, evidenced diffraction effects due to the presence of retained β-Ti in the AP sample, which plays a key role in the α→β solid state transformation occurring during the TT [21]. Figure 2 shows some of the considered samples during the SANS investigation.

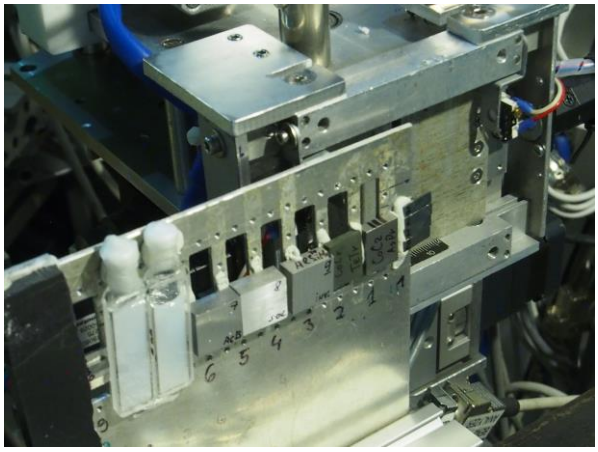

Figure 2. The Co25Cr5Mo5W and Ti6Al4V biomedical alloys samples produced by LPBF, during the SANS investigation.

Slika 2. Uzorci biomedicinskih legura Co25Cr5Mo5W i Ti6Al4V koje je proizveo LPBF, tokom istrage SANS-a.

Polyurethanes, as polymers containing the urethane linkage in their backbone chain, made by reacting di-isocyanates with di-alcohols, are commonly used in medical applications including catheters and general purpose tubing, hospital bedding, surgical drapes, wound dressings, as well as in a variety of injection moulded devices. Their most common use is in short-term implants. Figure 3 shows a concept model of a polyurethane mixture, in which the dimensional scales are indicative.

The amorphous zone has a joining action between the crystal zones; the bubbles, having a size ranging from 1 to 100 μm, can be closed or open and they change depending on mixing procedure, catalysis, temperature and material type. The crystal zone morphology is almost entirely ignored [22]. A current research is devoted to create flexible implants with improved characteristics based on polyurethanes with island plasma coating. A related problem is the possible fracture of the stiff solid coating, due to the mechanical load of the treated polymer. Important targets, thus, are the progress and the analysis of both soft polymers and their surface's coatings resistant to definite loads, with improved biomedical qualities as compared to the uncoated material. Structural analyses of a first group of polyurethane samples (mono-ethylene-glycol based) were performed at the nano(micro)-scale by SANS, showing the presence of different fractions and assessing the total area of fraction vs. bubble's radius.

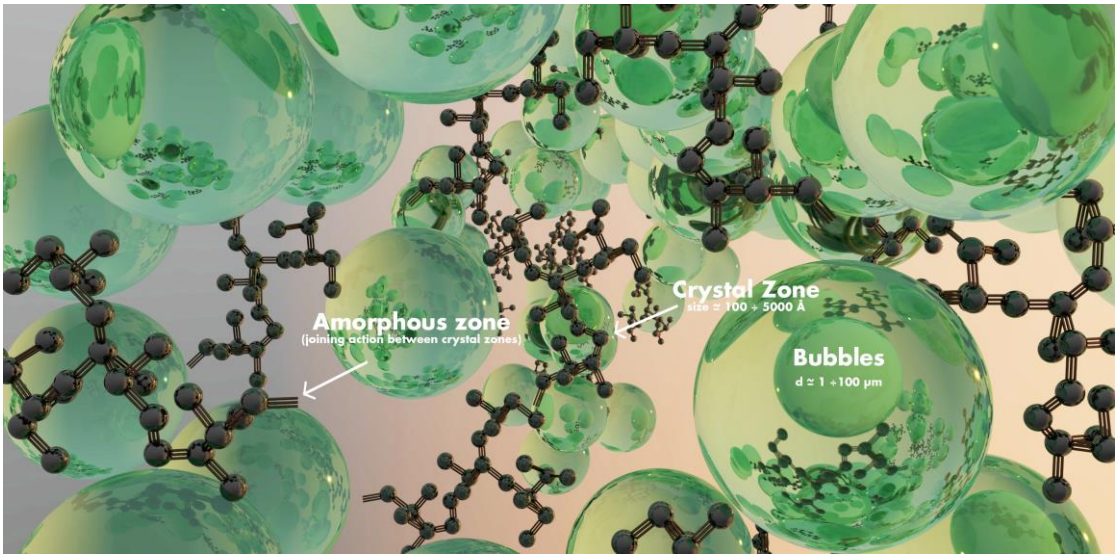

Figure 3. Concept model of a polyurethane mixture

Slika 3. Konceptualni model poliuretanske mešavine

Variation in chemical composition and technology of polymers resulted in bubbles' radii change. The small fractions appeared to be dominating, giving a large contribution to the interface area [22]. SANS helped then to characterize a second group of polyurethane samples, manufactured with varied known reactant mixture ratios with dissimilar branching levels and obtained from different zones of the production mould. A complicated structural organization of this material may have a strong influence on its functional properties: under certain conditions such as mechanical and thermal loading and aging, it leads to the material degradation, even in fresh-prepared bulk polymers and especially if defects are present in the material [23]. This kind of results helps to control and predict these functional properties, which strongly depend on size and amount of defects and especially on their total area detected by SANS.

Concerning the application of neutron crystallography for the structural analysis of biological molecules, finally, the following works can be mentioned: identification of charged amino-acids in protonation state from which the presence of a given hydrogen-bond can depend, in order to decipher the biological function; visualization of ligand/inhibitor binding modes or of specific protonation states of key catalytic residues; identification of the hydration pattern of the catalytic site; observation of intermediates steps along the catalytic reaction [24].

Further examples of applications of NBT in biology that can be mentioned, e.g., concern structure and dynamics of complex bio-membrane interactions [25], colloids for drug delivery [26], extracellular vesicles [27] and proteins [28, 29].

3. CONCLUSION

The applicability of NBT to the biomedical sector as non-destructive and non-invasive testing has offered more and more, in recent years, important information not available by any other method.

The results obtained by adopting NBT give a support in progressing features and production of biomedical materials and parts, e.g. metal alloys or polymers, specifically developed for biomedical applications: furthermore showing the usefulness of a multidisciplinary approach to fully investigate correlations between nano(micro)-structure and mechanical properties of the considered devices.

Complementary to the classical investigation methods, NBT can supply, furthermore, an important help both for the structural analysis of proteins and other bio-macromolecules and for improving existing materials and devices and producing original and innovative components for different types of applications, with optimization of quality, functionality and performance [30]. The near future can offer substantial room for new improvements for the optimisation, in general, of neutron instruments and techniques.

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IZVOD

Analiza biomedicinskih materijala i delova: napredna nano(mikro)-karakterizacija tehnikama neutronskog snopa

Napredak u proučavanju biomedicinskih materijala i uređaja, posebno zavisi od primene efikasnih tehnika karakterizacije za procenu ključnih fizičkih parametara vezanih za performanse, oštećenja i kvalitet. Glavni cilj je uspostavljanje tačnih odnosa između makroskopskih funkcionalnih svojstava i nano(mikro) karakteristika. Brojni invazivni biomedicinski uređaji, na primer, planirani da ostanu u ljudskom telu tokom celog života pacijenta, jednom implantirani, deluju u jonskom okruženju krvi i u kontaktu su sa oslobođenim supstancama i ćelijama. Posledični efekti se moraju dodati ostalim faktorima starenja: dinamički stres pulsiranja je jedan od ovih efekata i tiče se rada samoproširujućih stentova instaliranih u arterijama, kao što je karotida, da bi se ispravila stenoza. Tehnike neutronskog snopa su odlično sredstvo za proučavanje materijala i delova od biomedicinskog interesa, doprinoseći rešavanju važnih pitanja povezanih sa metodološkim ograničenjima opšte prihvaćenih metoda analize: njihovi rezultati, komplementarno, mogu pomoći u poboljšanju kvaliteta i funkcionalnosti. Ovaj rad se bavi naprednom nano(mikro)-karakterizacijom biomedicinskih materijala i delova ovim nedestruktivnim i neinvazivnim nuklearnim metodama. Pominju se i neki primeri koji se odnose na biološko polje. Za primenu u biomedicinskom i industrijskom sektoru, Inženjerska kancelarija Rogante je razvila posebne metodološke pristupe i namenske postupke obrade i tretmana.

Ključne reči: *biomaterijali, biomedicinski uređaji, tehnike neutronskog snopa, nanostruktura, mikrostruktura.*

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