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Advanced engineering materials and materials processing technologies in dental implant and prosthetic treatment with clinical cases

L.B. Dobrzański
Medical and Dental Engineering Centre for Research, Design and Production ASKLEPIOS, ul. Jana III Sobieskiego 12/1, 44-100 Gliwice, Poland
Corresponding e-mail address: dobrzanski@centrumasklepios.pl
ORCID identifier: https://orcid.org/0000-0002-4671-3060

ABSTRACT

Purpose: The article deals with materials science issues concerning the application areas in dental engineering. The monograph aims to present the results of the Author's work against the background of general achievements, indicating the engineering aspects of dental implant-prosthetic treatment. They include clinical cases, most often concerning complete edentulism, with a detailed discussion of the methodology of the material, technological, and structural design of dental prosthetic restorations, especially the impact of additive manufacturing conditions and surface engineering technology on the mechanical properties and structure of prosthetic restorations.

Design/methodology/approach: The monograph covering the engineering and technical activities of implant prosthetic treatment includes the Author's aspects concerning the development of the methodology of computer-aided design of dental prosthetic restorations and surgical guides ensuring their correct installation in the oral cavity of patients, along with virtual modelling of treatment plans, modelling of the load status of individual elements of implant-prosthetic systems, development of the methodology of computer-aided production of elements of the prosthetic restoration system as well as implants and implant-scaffolds with the use of milling technology in CNC centres and additive manufacturing by selective laser sintering, the results of research on the influence of additive manufacturing conditions on the structure and properties of titanium and its alloy Ti6Al4V and cobalt alloy Co25Cr5W5MoSi containing studies of biochemical properties for applications for implant-prosthetic purposes in dentistry, the results of tests on the influence of ALD atomic layer conditions on the structure and surface properties of metals and their alloys used in implant-prosthetic treatment in dentistry and the results of tests of prosthetic fillings used in the treatment of Tooth decay.

Findings: The basis for all the described achievements of the monograph are the comprehensive results of research related to the study of the structure and properties of engineering materials, especially titanium and cobalt alloys used in dentistry, subjected to additive manufacturing using the Selective Laser Sintering SLS method and surface treatment using the Atomic Layer Deposition ALD method, as a domain of materials engineering, in the context of the Industry Integrated Idea 3xI 4 model. 0/5.0 and the 6xE 6 Expectation Principle, which there is a paradigm for materials science. What is important in the approach are the results of biological tests of materials produced in such a way, leading to numerous applications in the Author's clinical practice in cooperation with dentists and the development of a general concept of a research, design, and production centre for prosthetic restorations and virtual acquisition of diagnostic data from cooperating dental clinics.

Research limitations/implications: The article is a monographic study referring to numerous of the Author's publications, patents, and presentations at scientific conferences and invention fairs, in which very extensive source information is provided concerning both a very large number of literature items and extensive factual material, including the results of materiallographic studies and descriptions of clinical cases, although this study also presents numerous aspects not yet published in any previous works.

Practical implications: The study presents, among others, detailed prosthetic and implant-prosthetic solutions implemented by the Author of the study and successfully used by patients. Although the study is formally qualified in the engineering and technical sciences in materials engineering, it has strong links with biomedical engineering and the applied area of interventional dentistry.

Originality/value: Numerous original publications, patent solutions, completed projects, and awards at the International Innovation Fair discussed in the monograph, as well as clinical experience related to the treatment of thousands of dental patients in our Author's clinic, confirm the originality of the approach and indicate the innovative nature of the achievements presented in the article so far. Many years of experience have led to the launch of a constantly developed production centre for prosthetic restorations and a virtual structure for obtaining diagnostic data from cooperating dental clinics. The article addresses scientists dealing with materials engineering applied in interventional dentistry and dental engineers in practice dealing with this issue.

Keywords: Materials engineering, Dental engineering, Additive manufacturing, Atomic layer deposition, Prosthetic restorations, Implants and implant-scaffolds, Implant prosthetic treatment, Titanium alloys, Cobalt alloys, Industry Integrated Idea 3xI 4.0/5.0, Industry 4.0, Dentistry 4.0, Prosthetic restoration manufacturing centre

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BIOMEDICAL AND DENTAL ENGINEERING AND MATERIALS

1. Introduction and purpose of the activities presented in the monograph

The words of Johann Wolfgang Goethe are the basis of the considerations contained in this review article, which contains the main Author's achievements from the past decade related to the creation of the company's own design, research, and implementation centre for medical and dental engineering, richly equipped with avant-garde technological devices and scientific and research equipment, as well as the organisation of a dynamic scientific team and multi-faceted research in this area "Knowledge alone is not enough, you also need to know how to apply it." The problems posed, even the opposite, must be addressed. In this context, the words of Marcus Tullius Cicero, "Usus magister est optimus" (Latin for "Practice is the best teacher"), take on a special meaning. Since it is necessary to apply knowledge daily, it should be systematically multiplied by one's own scientific research and numerous project and technological activities, presented in a condensed manner in this review article.

Modern medicine is closely related to and directly dependent on engineering support. A very broad scope is medical diagnostics, where, in addition to medical examinations, examinations of tissue fragments, e.g., blood, secretions, and excretions, as well as imaging and endoscopic examinations, requiring advanced electronic devices, play an important role in diagnosing diseases. Cardiac surgery and invasive cardiology, including cardiac catheterisation and angiocardiography, as well as coronary angioplasty, and increasingly intracoronary ultrasonography or postcoronary procedures within other vessels or heart valves, and interventions in the course of non-valvular heart defects, require specialised medical devices, including implants, e.g., stents and artificial heart valves, as well as surgical instruments produced in the processes of engineering. Trauma orthopaedics and other branches of surgery require numerous life support devices during surgery, numerous surgical instruments, and various implants, sutures, and many other medical devices. Dentistry is a special branch that uses numerous medical devices, including implants, prosthetic restorations, dental instruments and devices, and numerous diagnostic devices and devices necessary for dental treatment.

Dynamic technological progress related to, among others, the widespread implementation of the Industry 4.0 idea and the expected personalisation of the processes of designing and manufacturing implants, especially prosthetic restorations and surgical guides, requires very broad engineering and technical support for treatment conducted by a dentist. The basis of diagnostic tests is cone beam computer tomography (CBCT), which enables computer modelling of soft and bone tissues of each patient individually and, as a result, computer-aided design and production of prosthetic restorations and dental surgical guides, ensuring proper installation of implants in the patient's mouth during procedures performed by a dentist.

Among several aspects of the considerations included in this monograph, a prominent place is occupied by general theoretical considerations on the current stage of development of society and economy generally referred to as Industry 4.0 and Society 5.0, together with the Author's model 3xI Integrated Industry Idea 3xI 4.0/5.0 [1-5], where the concept of Dentistry 4.0 introduced in the world literature [6-9] plays an important role, indicating the importance of interventional dentistry and engineering activities as a result. Because of the attempt in the literature to depreciate activities of this type in favour of the monopolistic predominance of preventive activities in dentistry, the Author's model of Dentistry Sustainable Development was developed and widely disseminated [1-5, 8]. An important element of the model is the issue of the safety of dentists and medical personnel participating in dental treatment, which has become particularly important in the light of the SARS-CoV-2 pandemic and the resulting proprietary action and the developed design of appropriate devices to prevent infection [10-24].

Engineering and technical activities include the following original aspects discussed in this monograph:

- development of the methodology of computer-aided design of dental prosthetic restorations and surgical guides, ensuring their correct installation in the oral cavity of patients, in the face of atrophy of patients' dental processes, along with virtual modelling of treatment plans, modelling of the load status of individual elements of implant-prosthetic systems, m.in. using the finite element method [25-34];
- development of a methodology for computer-aided production of elements of the prosthetic restoration system as well as implants and implant-scaffolds using milling technology in CNC centres and additive manufacturing by selective laser sintering [7-9, 24, 35-43];
- investigations of the influence of additive manufacturing conditions on the structure and properties of titanium and its alloy Ti6Al4V and cobalt alloy Co25Cr5W5MoSi, including studies of biochemical properties for applications for implant-prosthetic purposes in dentistry [7-9, 24,35,36,38,39,41, 44-50];
- investigations of the influence of ALD atomic layer deposition conditions on the structure and surface properties of metals and their alloys used in implant-prosthetic treatment in dentistry [44,45,51,52];
- studies of prosthetic fillings used in endodontic caries treatment [53-56].

Due to the review-like nature of this study, it cites only its Author's publications, patents, and presentations at scientific conferences and invention fairs. At the same time, all very extensive source information concerning both numerous literature items and extensive factual material in the form of diagrams, tables, and numerous drawings, including materiallographic photographs and descriptions of clinical cases, are included in the works cited in this and only a few were used in it, including, m.in, the figures cited. The study also presents numerous aspects not published in any previous work.

The basis of the Author's work in the field of dental engineering related to the use of advanced technology in dental treatment, in particular in dental prosthetics and dental implantology, is the conviction that the most important thing is to take actions aimed at minimising the treatment area and the scope of interference with the patient's tissues, minimising the time necessary to perform the procedure to apply the lowest possible doses of agents anaesthesia and shortening the convalescence time after prosthetic and implant procedures to a minimum. At the same time, the methods and specific prosthetic solutions presented below allow for a significant increase in the availability of prosthetic and implant prosthetic solutions for patients who, due to having a minimal and degraded bone base, have so far been disqualified from the use of implant prosthetic restorations. Using lightweight and durable materials minimises the number of implants necessary. For treatment with a reduced number of implants to ensure the maintenance of implants in the long term, it is necessary to load the implants in the bone base properly. The Author of the study, because of many years of optimisation and analysis of the effectiveness of implant treatment conducted based on the patient base of the Author's dental practice, prefers implant placement, maintaining the parallelism of all implants to each other while maintaining the axiality of the insertion path concerning the occlusal forces acting on the bone-implant-prosthetic restoration system. Such a view contrasts the common all-on-4 solution, where arch implants in the lateral region are implanted at a significant angle, eliminating the need to rupture the bottom of the maxillofacial sinus and the need for bone regeneration procedures but requiring intermediate elements. In the approach presented in the study, the overriding engineering goal is to plan the treatment so that it is possible to assemble prosthetic elements directly from the implant level. As a result of many optimisations of the production process, which requires maintaining the accuracy of the mapping of the implant position concerning the design at the level of 0.1 mm and 4 degrees of deviation from the planned axis of insertion, the Author and his team effectively make full-arch restorations based on 6 or 8 implants as a monolith, i.e., a substructure integrated with individual abutments with all positioning hexagonal elements, the so-called hexes. The restorations allow for the elimination of any glued joints, and by maintaining constant access to the mounting screws, they also allow for multiple services of restoration over a long period of use without the need to destroy this work.

The study also presents detailed prosthetic and implant prosthetic solutions implemented by the Author of the study and successfully used by patients. Although the study is formally qualified in the engineering and technical sciences in materials engineering, it has strong connections with manufacturing engineering and the application area of interventional dentistry.

Indeed, the issues of health protection, the improvement of well-being, and the prolongation of human life are not only the domain of doctors and other medical professionals but are, in fact, the achievement of many different professional groups, although doctors are directly responsible for prevention and the results of treatment when it becomes necessary. Representatives of other non-medical professions, including biologists, psychologists, and, to a large extent, engineers of various specialities, actively participate in activities for the prevention, protection of health, and effective treatment of various diseases, including m.in common tooth decay. In the case of diagnosis and treatment of oral cavity diseases, including implant prosthetic and endodontic treatment, it is not the dentist who designs and manufactures implants and prosthetic restorations and the materials necessary for their production, as well as filling materials used in conservative dentistry and endodontics. The given review article concerns the design of engineering materials and their processing technology to produce implants, implant scaffolds, and prosthetic restorations for applications in dentistry and endodontic fillings. It is dedicated to dental engineers, materials engineers, and manufacturing engineers cooperating with them, but also to dentists, as well as doctors of other specialities, due to systemic complications that have their genesis in diseases of the oral cavity. The point is to enable the cooperation of the above-mentioned professional groups, strongly diversified in competencies and substantive interests, to synergise knowledge and activities beneficial to patients, whose good is at stake here. It is represented by the Author's model [54] created by analogy to a triangularly branched tree trunk, and the cross-section of the virtual trunk divided into three parts, symbolises the analysed aspects from three fundamentally different points of view, i.e., materials science, manufacturing engineering, and dentistry. They come from a common trunk, illustrated by centrifugal arrows pointing toward each other at an angle of 120°. To solve the problems, it is necessary to analyse the interesting aspects of the realities of each of the above-mentioned scientific disciplines, and they can neither be omitted nor simplified. A positive result of dental treatment should be understood as a specific virtual imaginary resultant vector from the summation of all the component vectors corresponding to the disciplines as mentioned earlier, for which the colours have been chosen respectively for each of the three points of view. Only the interaction and synergy of these factors can bring a positive result, and this symbolic virtual outcome vector will acquire both the right value and the direction and return, illustrating the synergy of materials science, manufacturing engineering, and dentistry with the hierarchical arrangement of the main analysed issues concerning materials and technologies used in dentistry. The discussed model is illustrated in Figure 1, fully justifying the importance of materials science in the context of the analysed issues.

Therefore, the monograph aims to present the results of the Author's work against the background of general achievements, indicating the engineering aspects of dental implant-prosthetic treatment, taking into account clinical cases, most often concerning complete edentulism, with a detailed discussion of the methodology of material, technological and structural design of dental prosthetic restorations, including, in particular, the influence of manufacturing conditions additive manufacturing and surface engineering technology on the mechanical properties and structure of prosthetic restorations. Particular attention was paid to the method of precise fixation of prosthetic restorations in the patient's oral cavity based on virtual design, along with the design and manufacture of so-called implant-scaffolds as porous or semi-porous medical devices, ensuring the growth of living osteoblast cells into these pores to ensure a strong connection between the living cells and the implanted medical device. Work in the area is well advanced and is still being continued. An approach to ensuring the high and reproducible quality of dental implant-prosthetic treatment through the virtual design of implant assembly and prosthetic restorations using prosthetic templates, as important elements of digital-dent dentistry, is also presented.

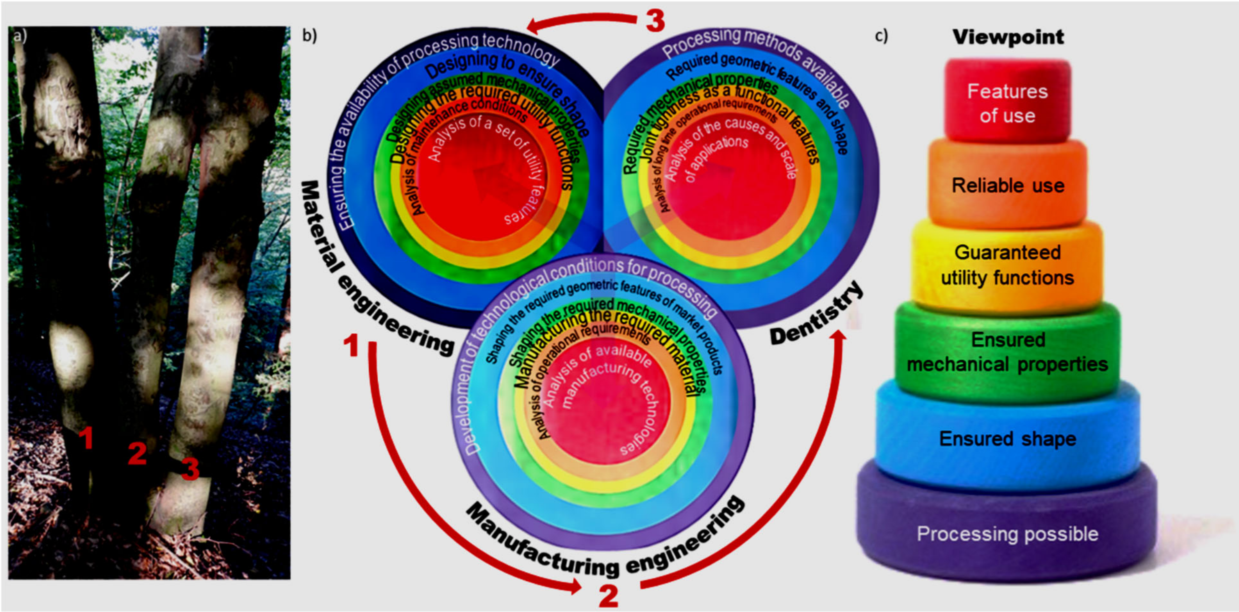


Fig. 1. An example of a triangularly branched tree trunk (a) with a synergy model of materials science, manufacturing engineering, and dentistry (b) together with a hierarchical arrangement of the main analysed issues concerning materials used in dentistry (c)

2. Author's theoretical analysis of modern industrial development

A major part of the Author's creative achievements is generalising the current state of technical activities. The general concepts of public good and social well-being are related to satisfying needs, most generally manifested by using multiple products in everyday life [1-5]. This process has a very long history, starting with the first attempts to use a simple stick and a sharp stone connected by grass fibres, which made it possible to use the spear produced in this way in hunting to satisfy the elementary needs of primitive tribes related to the feeling of hunger. Nowadays, it is impossible to catalogue human needs enumerative because of their multiplicity and diversity. The related dependencies can be expressed today as an octahedron P^2E^4 containing a consumer level covering human needs, meeting ecological conditions, meeting economic requirements, and ensuring the quality and reliability of products their consumers us.

On the other hand, the next octahedron of P^2M^4 illustrates the possibilities of making these products that serve humans. The technological level includes technical materials, most often engineering materials, i.e., obtained as a result of consciously developed technological processes, technological processes of their production and processing, appropriate machines and other technological devices, as well as highly developed control systems for the processes with increasingly advanced computer-aided technology, generally referred to as cyber-physical systems, thanks to which manufacturers can deliver the expected products to the market. Therefore, products are a common element of these two approaches – consumer and technological – as manufacturers produce more advanced products that meet more advanced customer requirements and expectations. In such a way, the original model of the Integrated Concept of Industry 3xI 4.0/5.0 (Fig. 2) [1-5] was created.

Using the coincident site approach (by analogy with the grain boundary model in polycrystalline material [1-5]), it is possible to distinguish four determinants centred around the products in the model, including technical materials and cyber-physical systems, as well as ecology and economics, as horizontal factors, combining these two approaches, technological and consumer, respectively. The three most important aspects of coincidental horizontal factors include developing engineering materials, the broad and multifaceted computerisation of all technological processes, the need to meet ecological requirements, minimise the environmental footprint, and the circular economy. The relevant model is presented in papers [1-5] (Fig. 3), and it was also adapted to the description of National Smart Specializations in Poland in materials and nanotechnology.

In light of the presented state of knowledge about the current state of development of the economy and society, a different view requires the model of Industry 4.0 [1-5] presented by H. Kagerman at the turn of the first and second decade of this century and popularised in 2016 along with the concept of the fourth industrial revolution by K. Schwab, the founder of the World Economic Forum (WEF). World Economic Forum at the summit in Davos, Switzerland industrial and social (Fig. 4).

In such a way, the concept of the development of Industry 4.0 has been significantly narrowed, starting from the implementation of the steam engine to advanced modern production control information systems. However, the importance of this important aspect must not be underestimated. On the other hand, the competitive Japanese model Society 5.0 includes five stages, from hunting culture through agrarian culture to a developed information society, reaching both of the models' comparable developmental stages of 4 or 5, respectively, characterising contemporary realities. At the same time, attention should be paid to the virtual nature of cyber-physical systems as the essence of the narrowed model, considering, among others, simulation and digital twins and six other information technologies. Undoubtedly, the products and the materials necessary to produce them belong to the realm of reality. Without materials, it is impossible to produce any product [1-5, 7,8, 38,39,42], and their selection and design have also evolved, now reaching the 4th stage of Materials 4.0 [1-5, 7,8,38,39, 42] (Fig. 5).

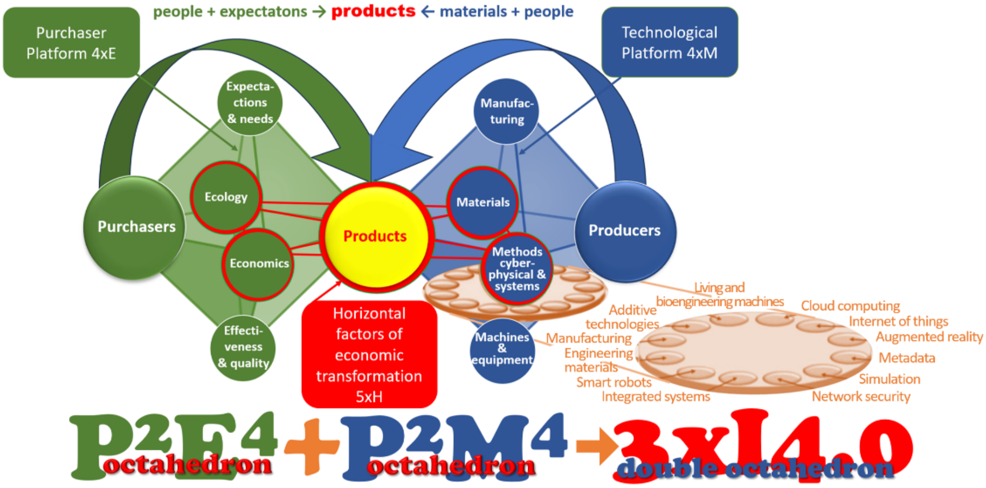


Fig. 2. Proprietary Industry Integrated Idea 3xI 4.0/5.0 model combining consumer and technological approaches through products manufactured as increasingly advanced by manufacturers to meet increasingly advanced customer requirements and expectations

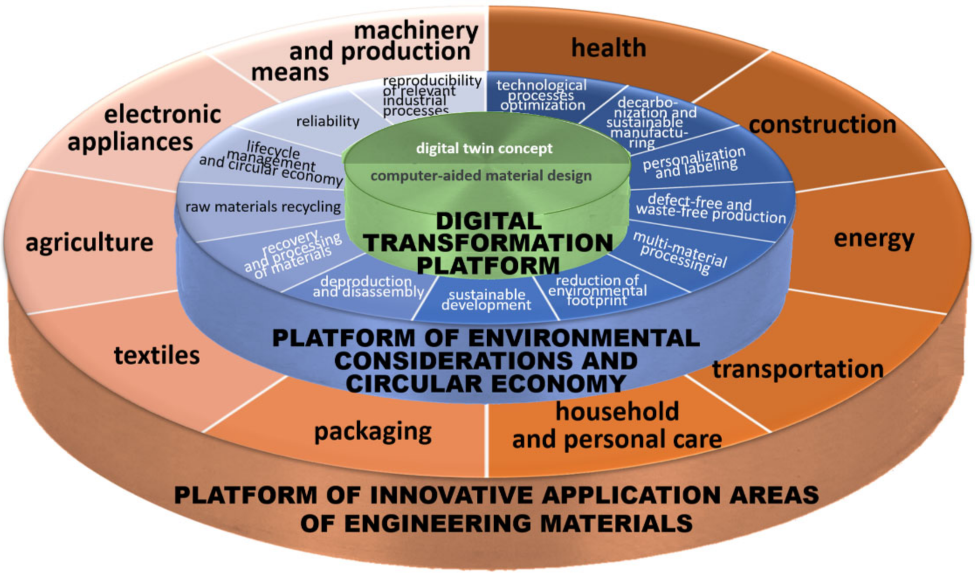


Fig. 3. The Author's model of the three most important aspects of coincidental horizontal factors concerning the development of engineering materials, widespread computerisation of technological processes, and minimisation of the environmental footprint

Technological processes are also undergoing an analogous evolution, reaching the Processes 4.0 stage, where, among others, an important role is played by additive manufacturing and advanced coating processes, including the application of ALD (atomic layers deposition). Therefore, the ongoing development processes can be described as Economy 4.0, and important technological processes related to it are described in detail in the Author's review papers [43,51,57,58].

The 6xE rule of six expectations governs the basis for selecting engineering materials for specific applications. To ensure the expected functional functions of a specific product, it is necessary to use the expected material, selected because of complex computer-aided design processes following the Material 4.0 rule, and subject it to the expected technological processes to give the expected shape and the expected structure, ensuring the expected physicochemical properties, guaranteeing the achievement of the expected functional functions of the product. On the other hand, it should be emphasised that the design of any product, including computer-aided with the use of computer modelling and artificial intelligence methods, as elements of a computer twin, consists of three inseparable and equally legitimate elements, i.e., material, technological and structural design (Fig. 6) [1-5, 8,42].

The relationships, as mentioned earlier, connecting the paradigm of materials engineering expressed by the 6xE principle of six expectations and the basic and inseparable elements of engineering design, including materials design and technological design, are the basis for all theoretical, cognitive, and research activities covered by the author's works carried out in the last decade and included in the given review article.

Fig. 4. The coincidence of temporal coincidence of the general development of society from the hunting culture to the contemporary super-computerised society with the model of industrial development from the age of steam to the contemporary industry based on cyber-physical systems in the models of Society 5.0 and Industry 4.0

3. Author's theoretical analysis of developmental foundations of modern dentistry and its engineering support

Among the important development goals set by the United Nations and upheld in the so-called 2030 Agenda [7-9, 39,42], SDG 3 is of great importance – health and well-being (Fig. 7).

Certainly, the reason for the interest in the following issues, especially those related to dentistry, needs to be explained. Dental diseases are an extremely important problem due to their prevalence on a global scale. Tooth decay, the inevitable consequence of partial and often complete edentulousness, affects 3-5 billion people worldwide [7-9, 39] (Fig. 8).

Unfortunately, according to the World Health Organization WHO [7-9, 39], Poland is one of the six countries most severely affected by this disease. The second disease that causes edentulism is periodontal disease, which determines the need to remove all teeth. The lack of teeth has a serious impact on the aesthetic aspects of the patient but also has a very negative impact on their overall health, as it can be the cause of about 500 systemic diseases, including heart attack, stroke, dysfunction of the cerebral hippocampus determining the loss of spatial orientation, as well as, for example, accelerated birth with fetal dysfunctions. There is no doubt that implant prosthetic treatment is necessary for medical indications. In this light, the approach of the authors of two papers in the Lancet is bizarre, as they believe that only prophylaxis in the field of dentistry is required, which does not stand up to criticism in any way and, therefore became the basis for the development of the Author's concept [1-5, 8] of integrated development of dentistry (Fig. 9).

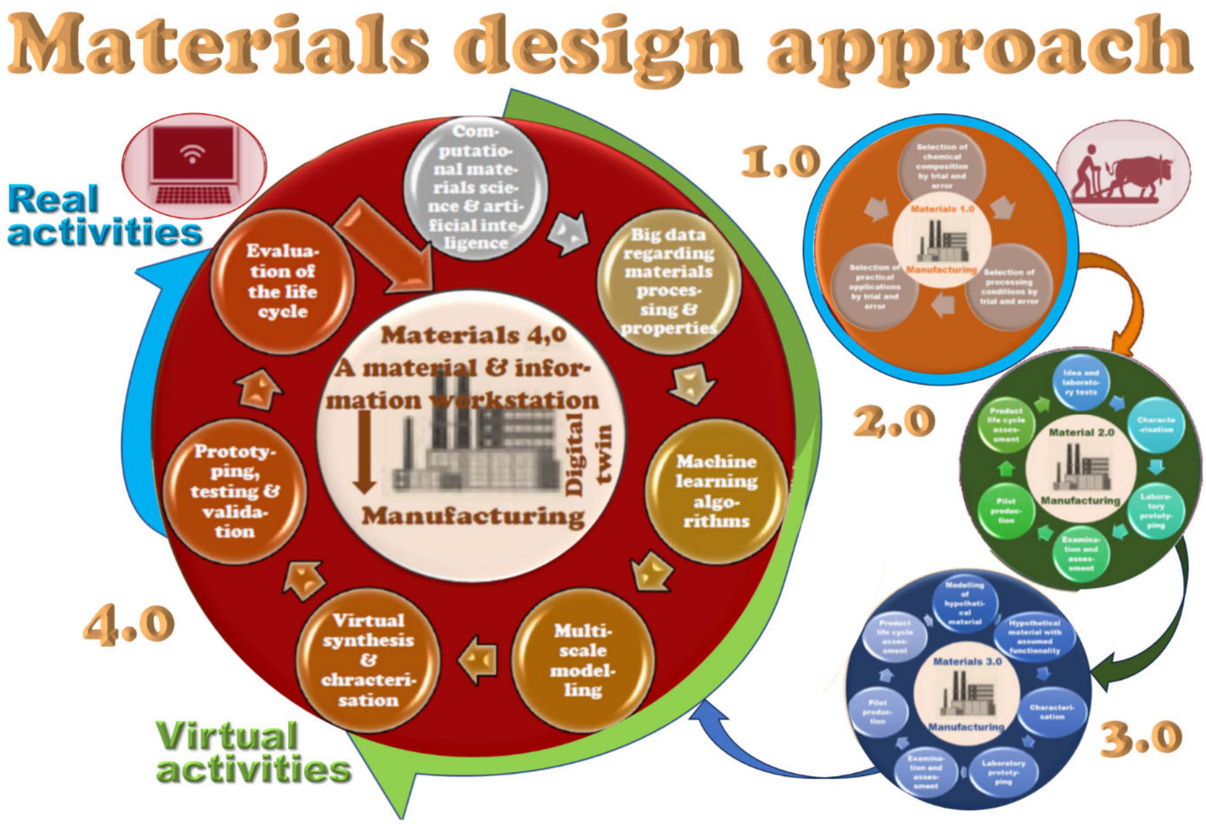


Fig. 5. The development of the approach to materials design in the period of development of human civilisation from the trial and error method of Materials 1.0, consisting entirely of real activities, through intermediate stages to the stage of Materials 4.0, consisting of a virtual approach requiring only experimental verification at the stage of implementation of the developed solutions

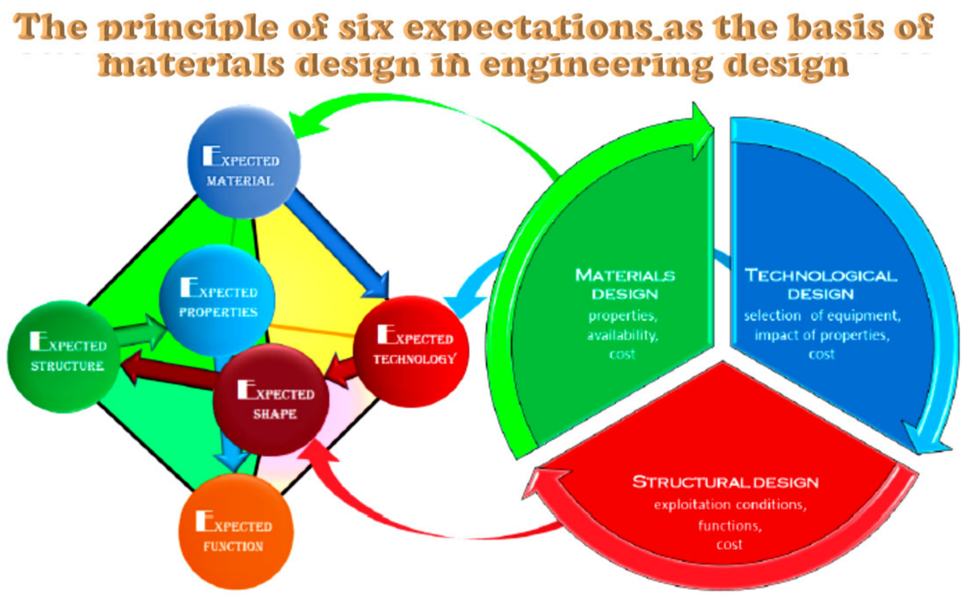


Fig. 6. The interplay of the three inseparable elements of engineering design comprising materials design, technological design, and structural design, and the principles of the six expectations of the 6xE constituting the materials science paradigm

The SARS-CoV-2 pandemic has shown that dentists and medical staff are particularly at risk of coronavirus droplet infection and other viruses originating from patients' breath. It became the basis for very intensive own work and the development of a special apparatus with a mask applied to the patient's mouth, in which negative pressure causes the viruses to be sucked out, and dentists are protected (Fig. 10). Author's patent has covered the device and has been recognised at invention exhibitions. This is an important element of the DSD 4.0 system as part of the Dentistry Safety System module [10-24].

It should be noted that the implementation of the basic principle applicable to every doctor, requiring compliance with the ethical principles contained in the Hippocratic Oath adopted on a global scale [6,59], places particularly high demands on dental engineers, who are responsible for the proper, high technical level of dental implants and prosthetic restorations applied to patients as a result of implant-prosthetic treatment. The aspects have been extensively considered in the Author's works [6,59] and illustrated in Figure 11.

It is unacceptable to use such a type of medical devices and devices made of, for example, materials with a toxic effect on the patient's body, such as Cr-Ni corrosion-resistant steel, or to use anachronistic technologies, e.g., casting, usually associated with an unacceptably high proportion of non-metallic inclusions and gas bubbles, significantly reducing mechanical properties, and increasing brittleness. Emerging literature reports indicating that the choice of technology is irrelevant in the given context and that anachronistic technologies are even preferred, result only from technological errors related to the lack of awareness of the authors of the papers that the desired properties of prosthetic restorations can only be obtained through a very careful selection of technological conditions, which was the subject of the Author's research [40,41], and of which the authors of the criticised papers are not the aware case, indiscriminately choosing the factory conditions of the technological process.

Fig. 7. Diagram of the scope of basic activities on good health and well-being under the 17 Sustainable Development Goals of the United Nations

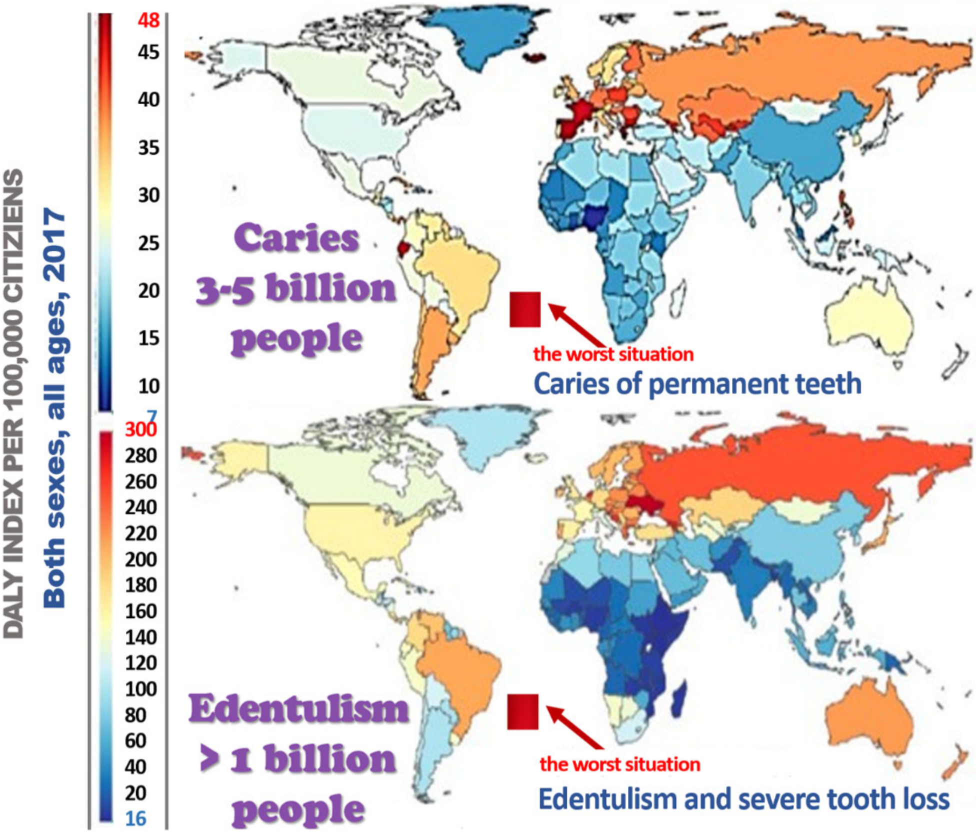


Fig. 8. Maps of the geographical variation of the disability-adjusted life years indicator DALY for 100,000 inhabitants by the severity of caries, regardless of the sex and age of the patients (top) and by the degree of edentulism, regardless of the sex and age of the patients (bottom)

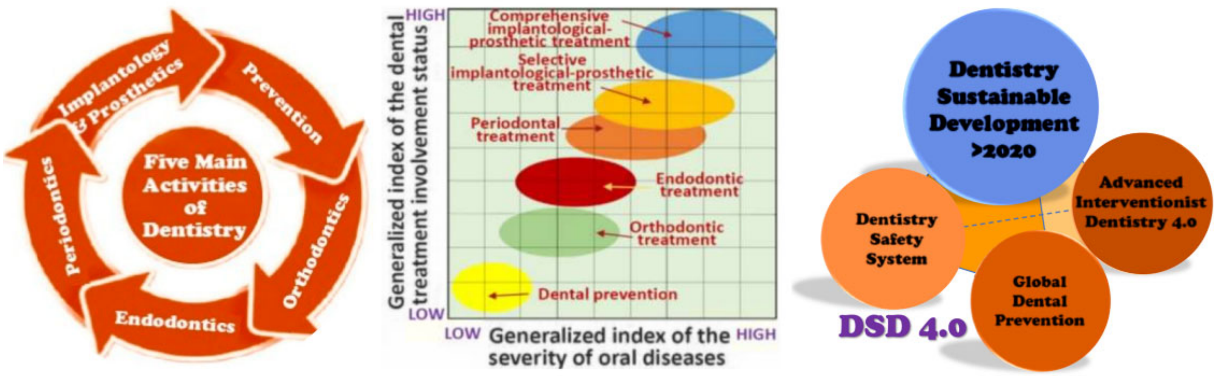


Fig. 9. Author's: diagram of the principles of the Five Main Activities of Dentistry (5MAD) (right), the concept of the matrix of advancement and treatment of oral diseases with the place of endodontics and implant prosthetic treatment (centre) and the model of the Dentistry Sustainable Development (right)

In the Author's publications [1-5, 42], it was pointed out that a highly developed developmental stage in dentistry and dental engineering has also been reached, referred to as Dentistry 4.0 (Fig. 12).

It is impossible to produce implants, and especially prosthetic restorations, including full-arch bridges, without the use of very advanced engineering materials, including titanium alloys [41] and over time non-resorbable magnesium alloys, with a density very similar to bone density [52], advanced surface engineering technologies [44,45,52], including the ALD method [44, 45,52] and advanced additive manufacturing technologies [40,41,52] and manufacturing, and additive manufacturing technologies, machining in numerically controlled CNC centres [24, 35-37, 41,46,52], with highly developed computer-aided design and manufacturing of CAD/CAM along with significant use of industrial artificial intelligence [52], as well as virtual design, among others using the finite element method (FEM) [25].

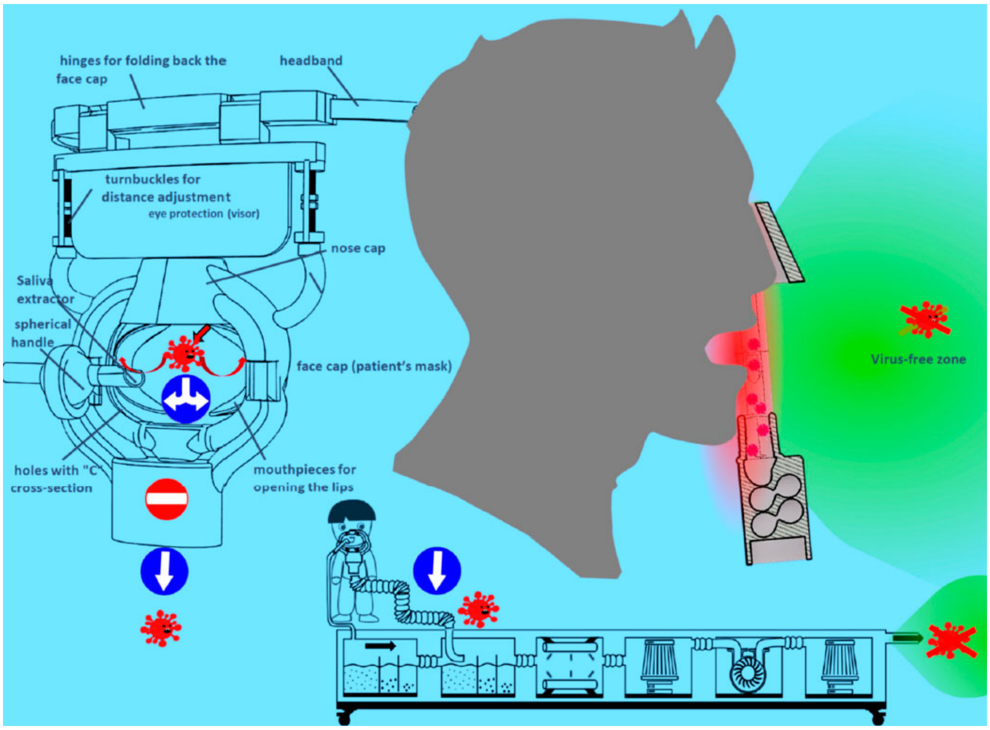


Fig. 10. Diagram of the breakthrough Author's devices to ensure the safety of the dentist by eliminating clinical aerosol of the SARS-CoV-2 virus at the source by negative pressure aspirating bioaerosol at the patient's mouth line

Additive technologies are used to manufacture various implants, including dental implants and bridges, individual implants of the mandibular bone, of the hip joint, and skull fragments [7-9, 24, 35-37, 39-42, 47-50, 52, 60-66]. The exceptional usefulness of additive manufacturing technologies for solid and microporous materials in medicine and dentistry has been confirmed in the Author's works by comparing powder metallurgy, foundry, metallic foam using the methodology of knowledge engineering, including technological foresight, especially procedural benchmarking [43,51,57,58]. Expert opinions were used for the comparative assessment, using a universal scale of relative states, in which the value of 1 is the minimum assessment or level of agreement with a given feature/phenomenon/factor/

statement. At the same time, 10 is an extremely high rating or level of such an agreement. Based on technological experience, the individual criteria were weighted accordingly in assessing the potential, constituting an objective measure of the value of each of the selected technologies and the attractiveness corresponding to the manufacturer's impression of its value (Fig. 13).

Among the most commonly used additive technologies in the industry [43,51,57,58] include stereolithography (known as STL), laser metal deposition (LMD/LENS/DMD), three-dimensional printing (3DP), photocured resin shooting (PJ/PJM), production of laminated models (LOM), deposition of fused material (FDM), in dental prosthetics, only a few, i.e., electron beam melting (EBM), as well as three-dimensional printing for the production of intermediate models, have been used. However, the greatest possibilities are offered by selective laser sintering/melting (SLS/SLM) [57].

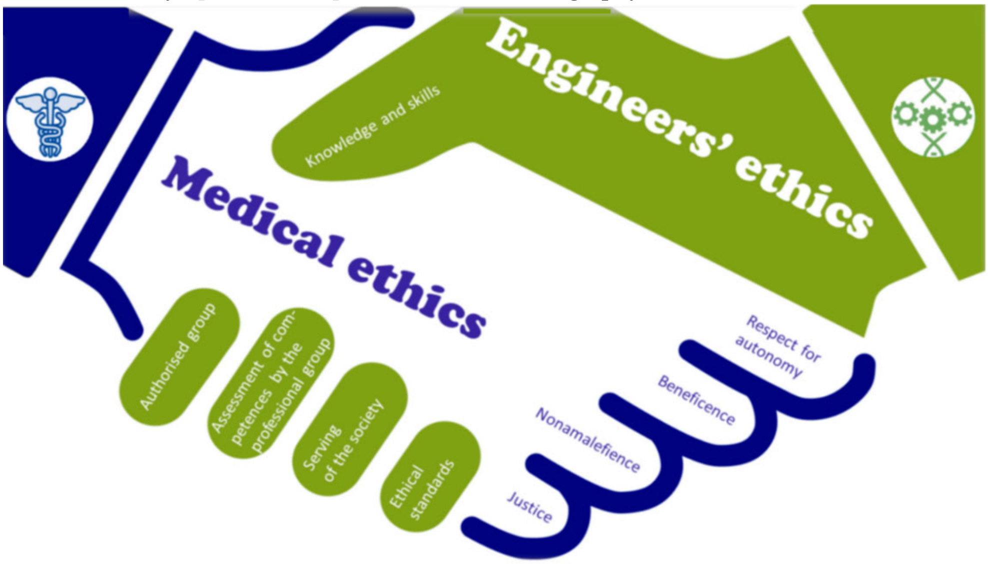


Fig. 11. A diagram of the coexistence of ethical principles binding physicians and dentists and the bioengineers and dental engineers cooperating with them, symbolised by the handshake of a physician and an engineer

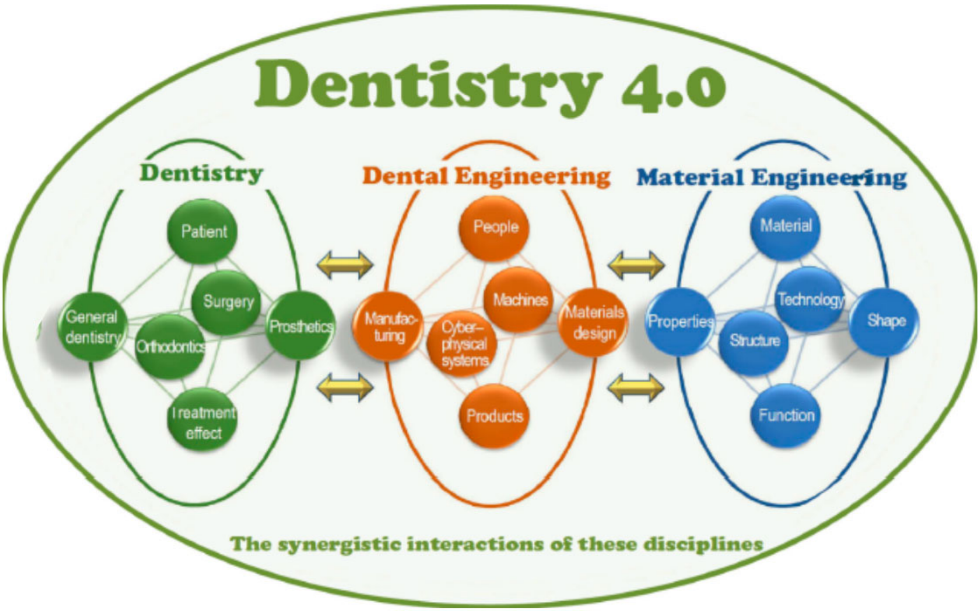


Fig. 12. General diagram of the Dentistry 4.0 model showing synergistic relations between dentistry, dental engineering, and materials engineering

The results of the above-mentioned theoretical analysis became the premise for the extensive empirical research undertaken by the company, consisting of the optimisation of the structure and properties of metal alloys most commonly used in dentistry, i.e., titanium and its alloy Ti6Al4V and cobalt alloy Co25Cr5W5MoSi subjected to various technological processes of production and processing included in the following parts of this review article.

4. Investigations of the influence of additive manufacturing conditions on the structure and properties of solid titanium and its alloy Ti6Al4V and cobalt alloy Co25Cr5W5MoSi

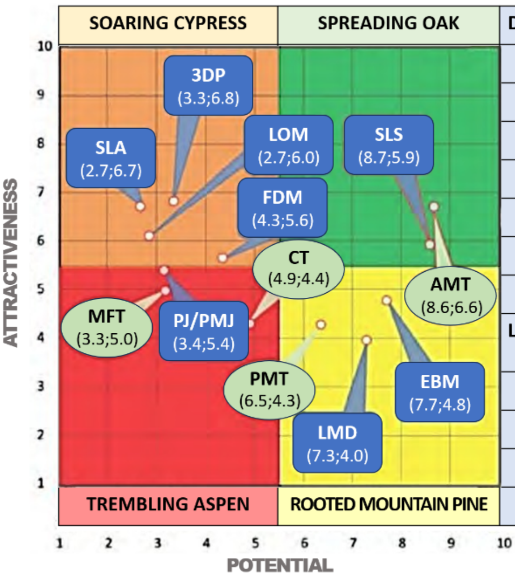
Extensive studies of the influence of additive manufacturing conditions on the structure and properties of titanium and its alloy Ti6Al4V and cobalt alloy Co25Cr5W5MoSi have been carried out using numerous methods of materials science research, largely published in the Author's papers [40,41]. As a standard, the Author developed micro specimens for testing mechanical properties in static tensile and bending (Fig. 14), and compression tests were adopted.

The properties of numerous materials [25] that can be used in dentistry have been compared by conventional technologies from blocks supplied for milling in a numerically controlled CNC centre and by additive manufacturing by selective laser sintering.

A comparison of properties (Fig. 15) shows that the highest possible values of tensile and flexural strength are shown by the Ti6Al4V alloy produced by selective laser sintering, compared to Co-Cr alloys and titanium produced by the same method, compared to the milled Ti6Al4V alloy, when the strength of zirconium dioxide ZrO_2 is several to several times lower (Fig. 15). Porous materials produced by selective laser sintering exhibit properties correspondingly lower depending on the pore diameter (Fig. 15c,d).

In addition to standard micro specimens, a proprietary standard of specialised micro specimens for bending tests [25] corresponding to 3 types of selected three-point dental bridges has been developed (Fig. 16b). In this way, the micro specimens produced from different materials produced by milling in a CNC centre and alternatively selectively laser sintered were subjected to static bending tests, shown in Figure 16a. Finite element modelling results for both Ti6Al4V and Co25Cr5W5MoSi alloys (Fig. 16c,d), indicating the maximum critical stresses in the zone of abutments connecting the middle tooth with the abutment teeth.

Figure 17 presents selected results of stereoscopic microscopy tests of damage to micro specimens for bending tests corresponding to 3 types of selected three-point dental bridges resulting from the tests [25]. The results of the studies confirm the modelling [25] that the connection of material abutments with abutment teeth is the stress concentrator, which resulted in cracks or complete decohesion in the given places. It should be noted that with slight destressing, complete decohesion of bridges made of zirconium oxide occurs, indicating the extremely limited suitability of the material for applications in dental prosthetics despite its highly valued aesthetic qualities. Based on the presented research results, using zirconium oxide only as a base for prosthetic crowns and



Designation	Technology type
PMT	Powder metallurgy technologies
CT	Casting technologies
MFT	Metal foam technologies
AMT	Additive manufacturing technologies
SLA	Stereolithography
SLS	Selective laser sintering
EBM	Electron beam melting
LMD/LENS/DMD	Laser metal deposition/laser engineered net shaping/ direct metal deposition
3DP	Three-dimensional printing
PJ/MPJ	Particle jetting/micro-particle jetting
LOM	Laminated object manufacturing
FDM	Fused deposition modeling

Fig. 13. Dendrological matrix of technologies for powder metallurgy, foundry, metallic foam manufacturing, and additive manufacturing useful in medicine and dentistry to produce solid and microporous materials

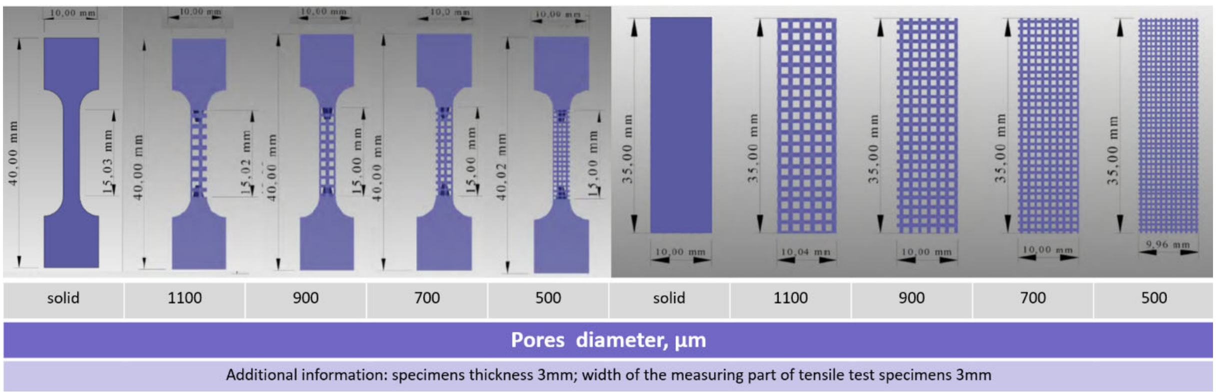


Fig. 14. Schematic diagram of solid and porous micro specimens for mechanical properties testing in static tensile and bending tests

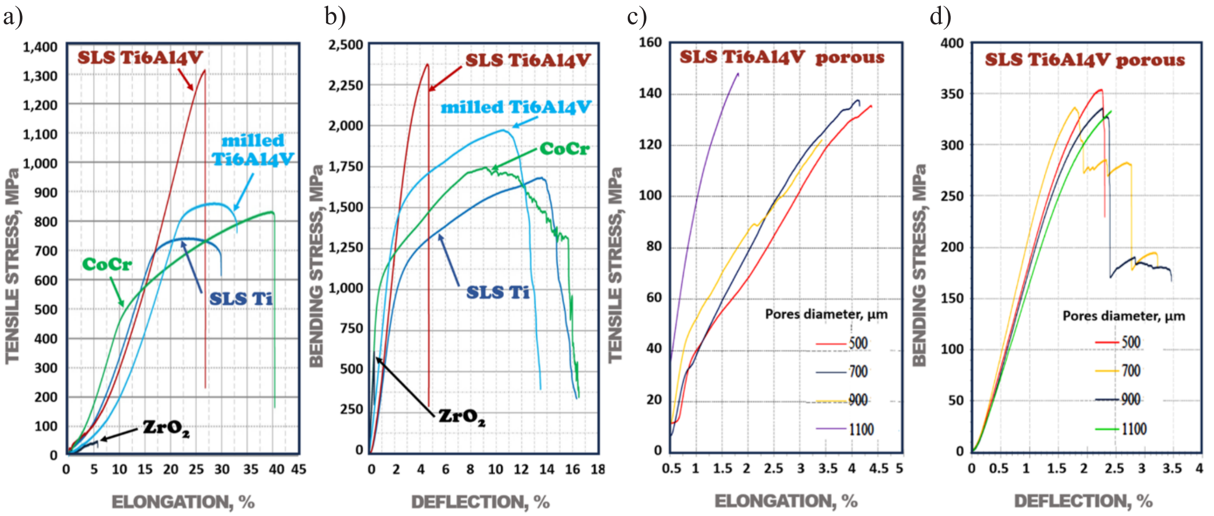


Fig. 15. Dependence of tensile and flexural strength of solid (a,b) and porous (c,d) micro specimens with different pore diameters on the elongation or deflection of different materials used in dentistry for implants and/or prosthetic restorations, respectively

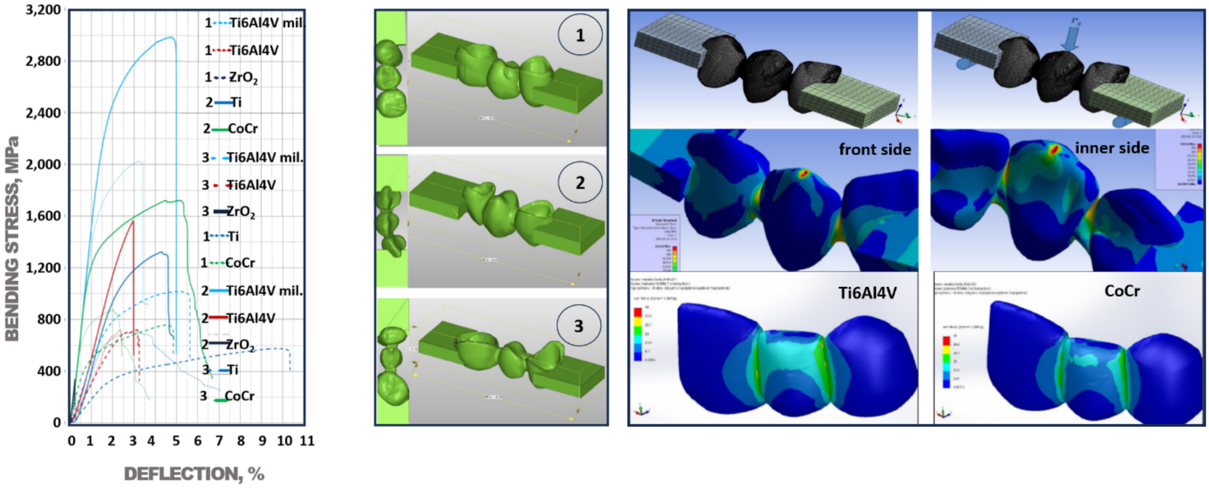


Fig. 16. Static tensile diagrams (column on the left) of specialised micro specimens for bending tests corresponding to 3 types of selected three-point dental bridges (column second from the left) and exemplary results of finite element modelling for Ti6Al4V and Co25Cr5W5MoSi alloys

non-extrusion 3-point bridges seems reasonable. However, the material has insufficient mechanical properties to be used as a base for extensive full-arch works, particularly with bridge spans containing more than one tooth. When using the material as a base for crowns, it is also recommended to use the so-called 3/4 crowns, which ensure the highest occlusal forces at the point of contact on the occlusal surfaces and the cross-section of the crown is much larger than the minimum thickness of 0.6 mm.

The results of the preliminary strength tests [25] constituted an important premise for the continuation of very detailed studies of the influence of additive manufacturing conditions on the structure and properties of titanium alloy Ti6Al4V and cobalt alloy Co25Cr5W5MoSi, justifying the widespread use of these alloys in dental implant-prosthetic treatment [40,41].

Detailed investigations of the mechanical properties of both selected alloys Ti6Al4V and Co25Cr5W5MoSi were carried out depending on the widely diversified conditions of selective laser sintering in connection with the changes in the structure, which fundamentally determine the properties following the paradigm of materials engineering defined by the 6xE principle of six expectations, indicating, m.in, that the technological processes to which the tested materials were subjected by giving an appropriate structure, ensuring the expected mechanical and physicochemical properties.

Figures 18 and 19 refer to the tensile and flexural strength of Ti6Al4V, respectively. Depending on the selection of selective sintering conditions given in the table constituting a fragment of the figure on the right, the strength of Rm differs more than twice from 554 to 1551 MPa. On the other hand, the flexural strength is in the range of 1099 to 2464 MPa (Fig. 18).

In the case of the Co25Cr5W5MoSi alloy, there is a significant variation in the tensile strength between 276 and 912 MPa and the flexural strength between 255 and 1467 MPa, depending on the selective laser sintering conditions (Fig. 20).

Different conditions of selective laser sintering, influencing, as shown above, affect the mechanical properties, as shown above, depending on the significant variation in the structure of the alloys studied.

The input material is the powder of both mentioned materials, shown in Figure 21.

As a result of selective laser sintering, in each of the tested alloys, there is a solid solution structure (Fig. 22), and the Ti_3Al phase as well as Co_3W and Co_3Mo phase, respectively, which is confirmed by a detailed X-ray analysis after selective laser production.

By studying the structure of thin films in the high-resolution transmission electron microscope (HRTEM), it has been shown that the structure of both titanium and Ti6Al4V alloy produced by selective laser sintering, regardless of whether they are solid or porous materials is strip martensite identified by diffraction as the α-Ti phase (Fig. 23), which was also confirmed by the above-mentioned results of X-ray analysis.

Very detailed structural studies indicate that the laser power density and the selection of numerous other technological conditions determine the materials'

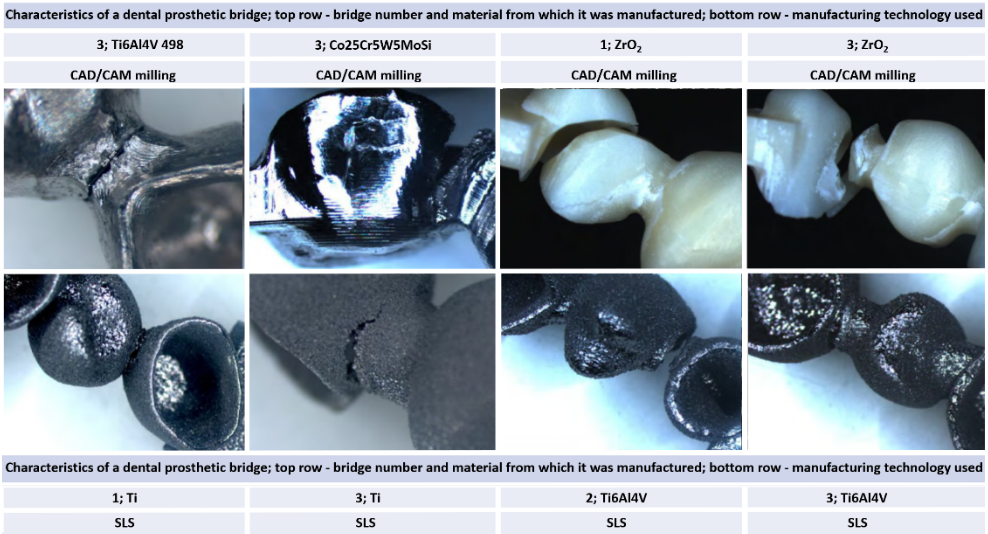
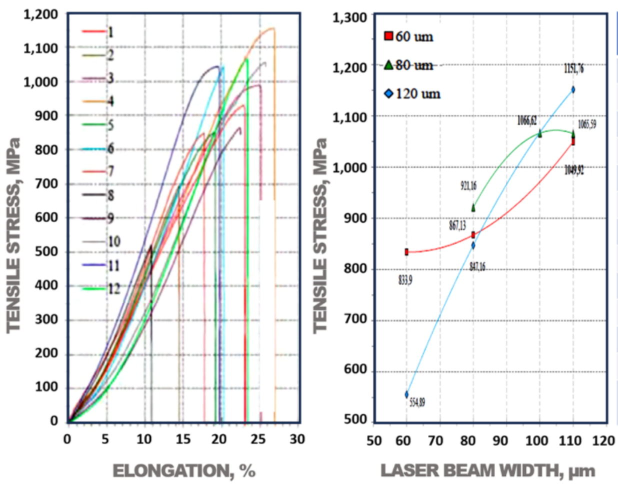
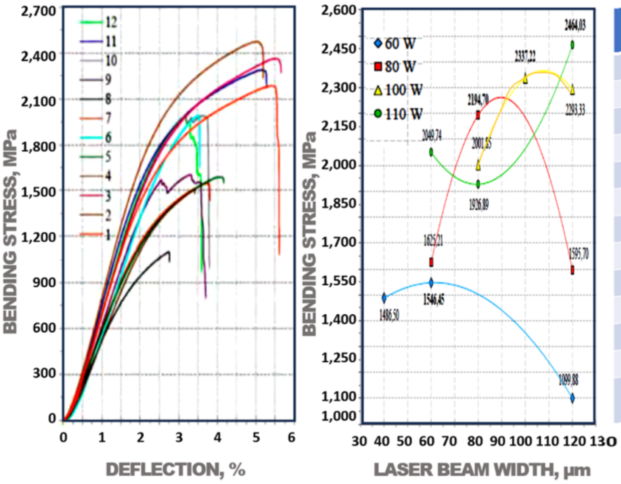


Fig. 17. Results of materialographic observations in a stereoscopic microscope of damage to micro specimens made of titanium, Ti6Al4V, and Co25Cr5W5MoSi alloys and ZrO_2 zirconium dioxide, respectively, produced by CNC milling or selective laser sintering, respectively, for bending tests corresponding to 3 types of selected three-point dental bridges resulting from static bending tests



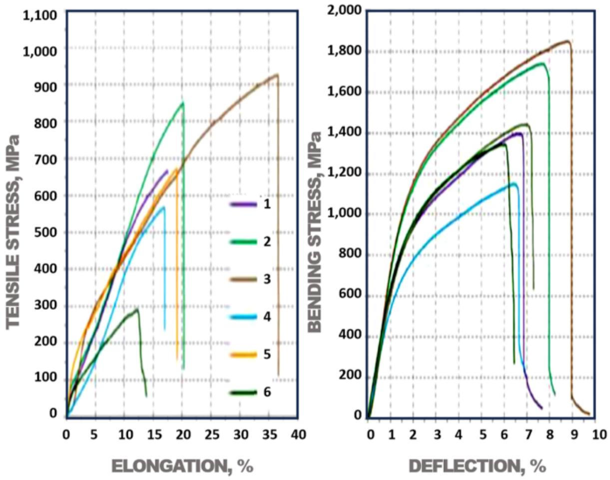
Ti6Al4V alloy No	Laser power, W	Laser spot diameter, µm	Laser beam width, µm
1	80	40	80
2	60	40	40
3	100	40	100
4	110	40	120
5	80	40	120
6	110	40	60
7	60	40	60
8	60	40	120
9	80	40	60
10	100	40	80
11	100	40	120
12	110	40	80
Scan speed - 630mm/s; powder thickness – 25 µm; finishing allowance – 10%			

Fig. 18. The tensile strength of Ti6Al4V alloy depends on the conditions of selective laser sintering, as indicated in the table on the right



Ti6Al4V alloy No	Laser power, W	Laser spot diameter, µm	Laser beam width, µm
1	80	40	80
2	60	40	40
3	100	40	100
4	110	40	120
5	80	40	120
6	110	40	60
7	60	40	60
8	60	40	120
9	80	40	60
10	100	40	80
11	100	40	120
12	110	40	80
Scan speed - 630mm/s; powder thickness – 25 µm; finishing allowance – 10%			

Fig. 19. The table on the right indicates that the flexural strength of Ti6Al4V alloy depends on the conditions of selective laser sintering



Co-Cr alloy No	Laser spot diameter, µm	Laser beam width, µm	Finishing allowance, %
1	40	120	0
2	40	80	0
3	40	80	10
4	80	120	0
5	40	120 alt	0
6*	40	100	10
Laser power – 105W; scan speed - 630mm/s; powder thickness – 25 µm; alt- adjust line thickness; *Ar flow too small			

Fig. 20. Tensile and bending diagrams of selectively laser-sintered Co25Cr5W5MoSi alloy under the conditions indicated in the table on the right

correctness or structural defects due to selective laser sintering. The main structural effect of the correct or incorrect selection of the technological conditions is porosity, which, as indicated in Figure 24, ranges from 0.06 to 10.53% because of the examination of the surface fraction on metallographic specimens in a light microscope at a standard magnification of 100 times (Fig. 24).

The structure of the investigated alloys indicates a band system resulting from significant selective laser sintering. At the same time, observations at higher magnifications in scanning electron microscopy of fractures after tensile and bending tests indicate the presence of completely unmelted fine carbides as a result of too low density of the laser beam (the first two columns in the case of the Ti6Al4V alloy (Fig. 25) and the first column in the case of the Co25Cr5W5MoSi alloy (Fig. 26), which, at an even higher magnification, is revealed in the form of unmelted spherical particles emanating from a niche formed by larger and interconnected powder grains as a result of sintering processes. (third or second column, respectively). It indicates an improperly executed selective laser sintering process. The fourth column shows an example of a properly performed selective laser sintering process, where no unmelted powder grains are observed at the breakthrough. In the bottom row, the structures of fractures obtained in tensile tests with visible fine powder grains that have not melted due to selective laser sintering can be seen. Such effects are not observed in the case of a properly performed selective laser sintering process (last column, bottom row).

A full set of performed studies enabled the development of an original generalised model of selective laser sintering (Fig. 27) [1-5, 67]. Following R. German's suggestion, the basis is to demonstrate that the process is carried out by sintering with the participation of the liquid phase. Too high density of the laser beam leads to the simultaneous melting of several layers of powder, including the one that has already been melted in previous passes of the laser beam. Apart from the economic inefficiency of the process carried out under such conditions related to the excessive use of power, it usually results in the bending and warping of the manufactured element due to significantly excessive thermal stresses. Avoiding the associated problems required laser power during the trials to reduce the density and, consequently, the laser power. Excess laser power also led to the "burning" of the surface of the sintered element. As indicated by the developed model, the laser power and, consequently, the heating power density should be selected in such a way as to lead to epidermal heating of the last layer of powder and only the surface of the previously sintered layer, which guarantees the

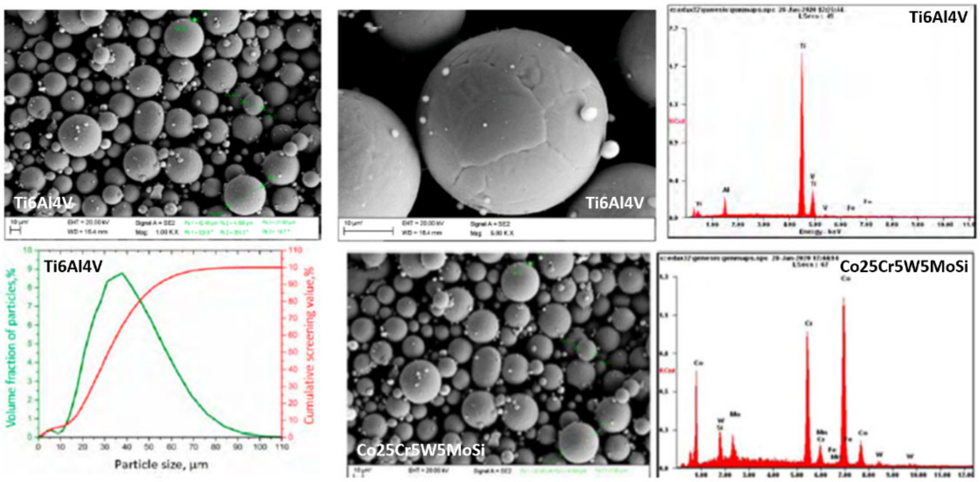


Fig. 21. The structure of Ti6Al4V and Co25Cr5W5MoSi powder, respectively, observed in scanning electron microscopy together with the results of the study of their chemical composition by the EDS method

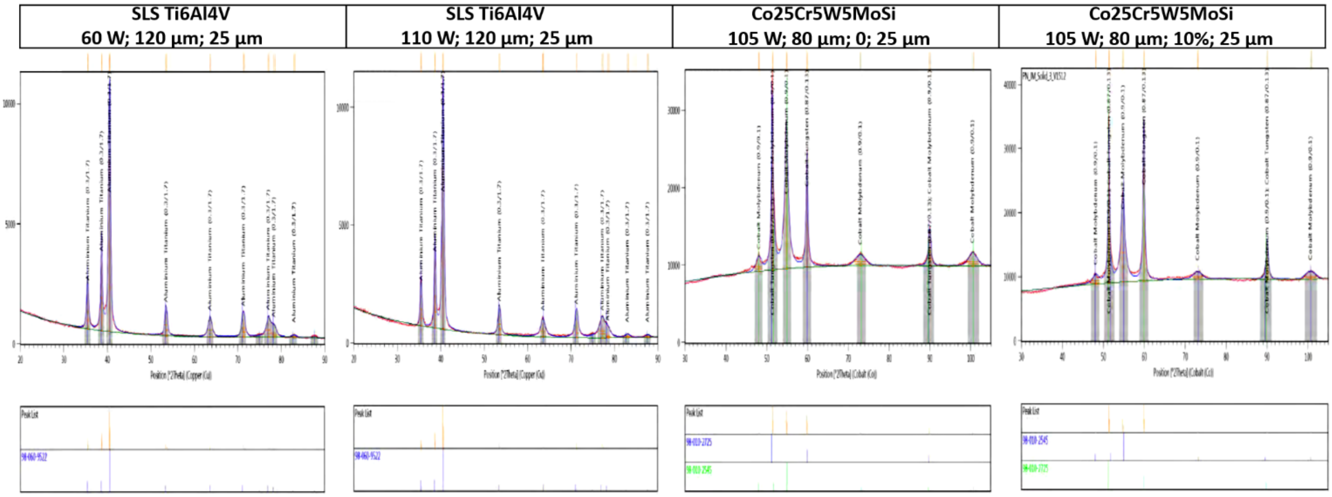


Fig. 22. X-ray diffractograms of alloys Ti6Al4V and Co25Cr5W5MoSi produced under various selected conditions by selective laser sintering

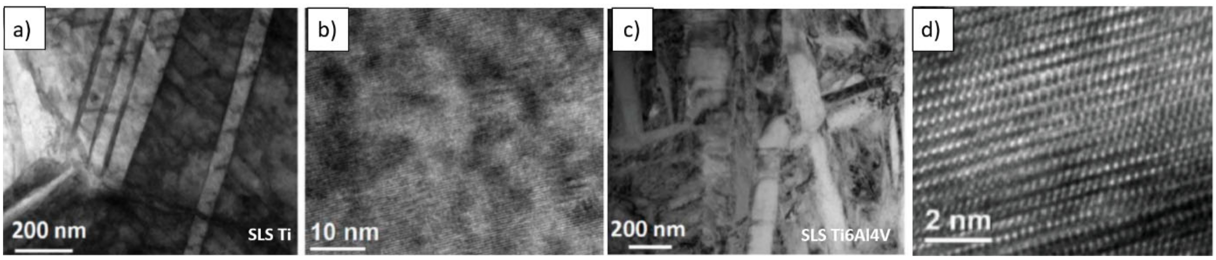


Fig. 23. The crystalline structure of strip martensite in thin films observed under high-resolution electron microscopy in pure titanium (a,b) and Ti6Al4V alloy (c,d) produced by selective laser sintering

most favourable mechanical properties and structure of selectively laser-sintered materials. Due to the powder's size variation resulting from its distribution (cf. Fig. 21), the finest powder particles are most likely to be completely melted in such conditions. In contrast, most ones of medium size or larger are only subject to surface melting, which ensures partial melting following the mechanism of the participation, not dominance, of the liquid phase in the sintering processes.

5. Investigations of selected physico-chemical properties of additively produced titanium alloys Ti6Al4V and cobalt Co25Cr5W5MoSi

Tests of pitting corrosion resistance were carried out using the potentiodynamic polarisation curve registration method [52]. The tests were performed at room temperature in different aqueous environments, as shown in Table 1.

Corrosion tests were carried out in two stages:

- determination of the open circuit potential (E_{ocp}) for 1 hour;
- registration of anode bias curves from the potential E start = E_{ocp} - 100 mV until the potential reaches the value of 2 V or the current reaches the value of 1 mA/cm^2, with a potential increase rate of 1 mV/s, and then the return curve is recorded in the potential E_{start}.

With the use of the Tafel method, the characteristic electrochemical values of the materials were determined:

- J_{KOR} – plate current density;
- E_{kor} – corrosive potential;
- R_{pol} – polarisation resistance.

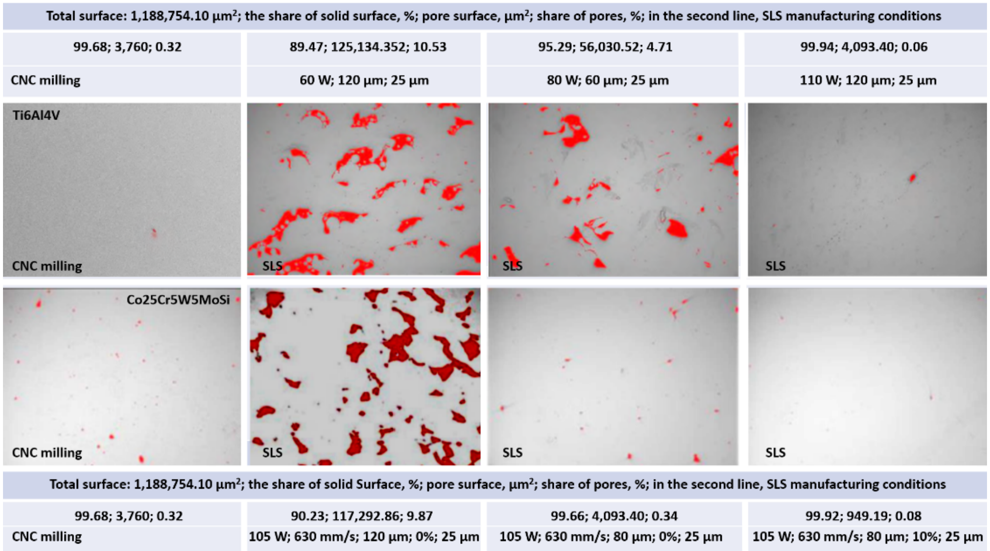


Fig. 24. Examples of the surface fraction of pores in alloys Ti6Al4V (top row) and Co25Cr5W5MoSi (bottom row) after standard milling (first column) and selective laser sintering under incorrectly selected (middle columns) and optimally (last column) conditions

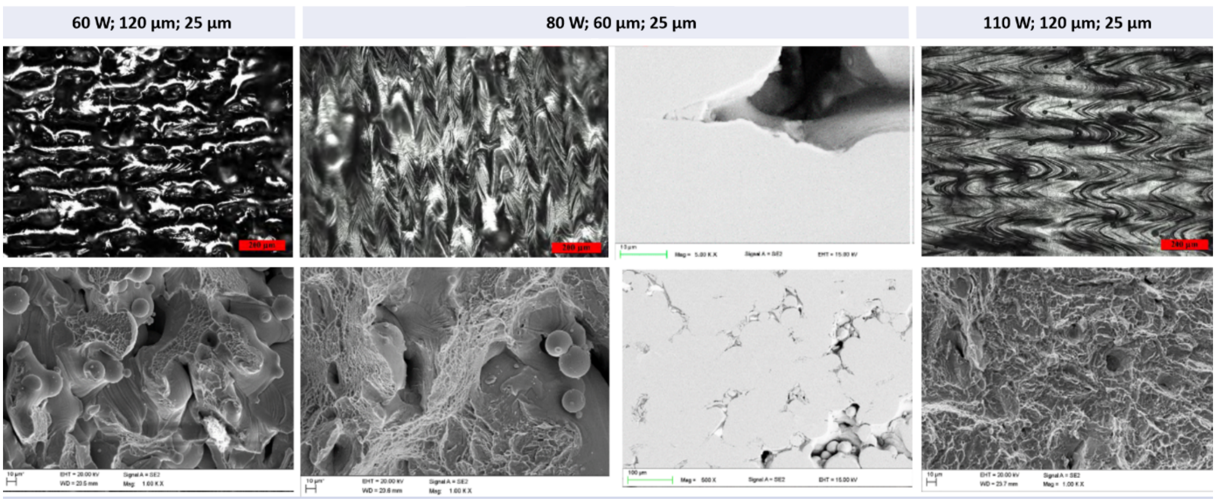


Fig. 25. Examples of Ti6Al4V alloy structure after selective laser sintering under incorrectly selected conditions (three columns on the left) and under optimal conditions (column on the right)

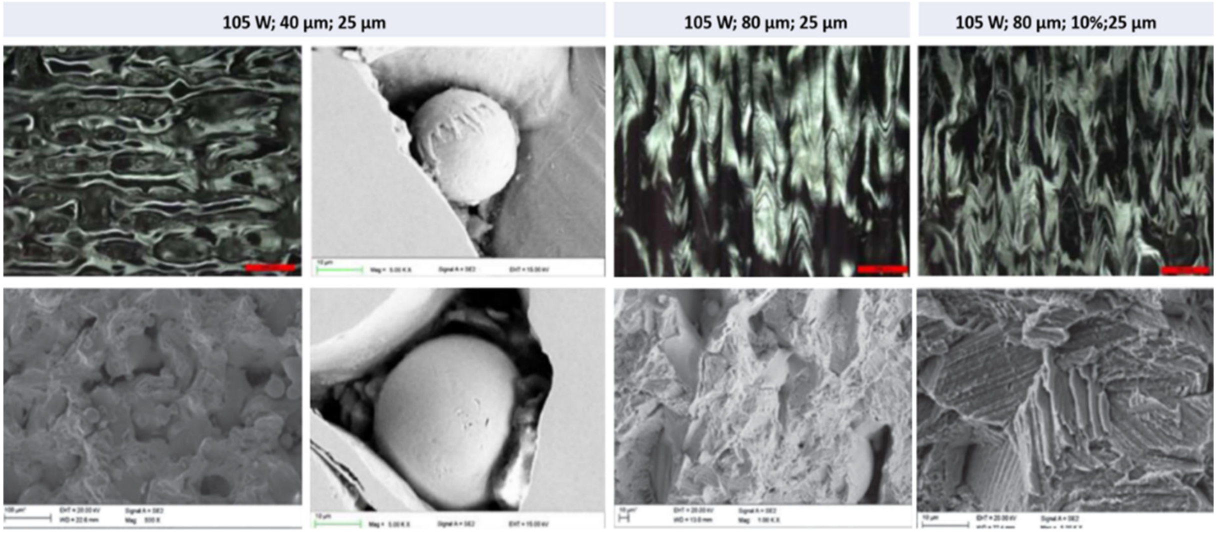


Fig. 26. Examples of Co25Cr5W5MoSi alloy structure after selective laser sintering under incorrectly selected conditions (three columns on the left) and under optimal conditions (column on the right)

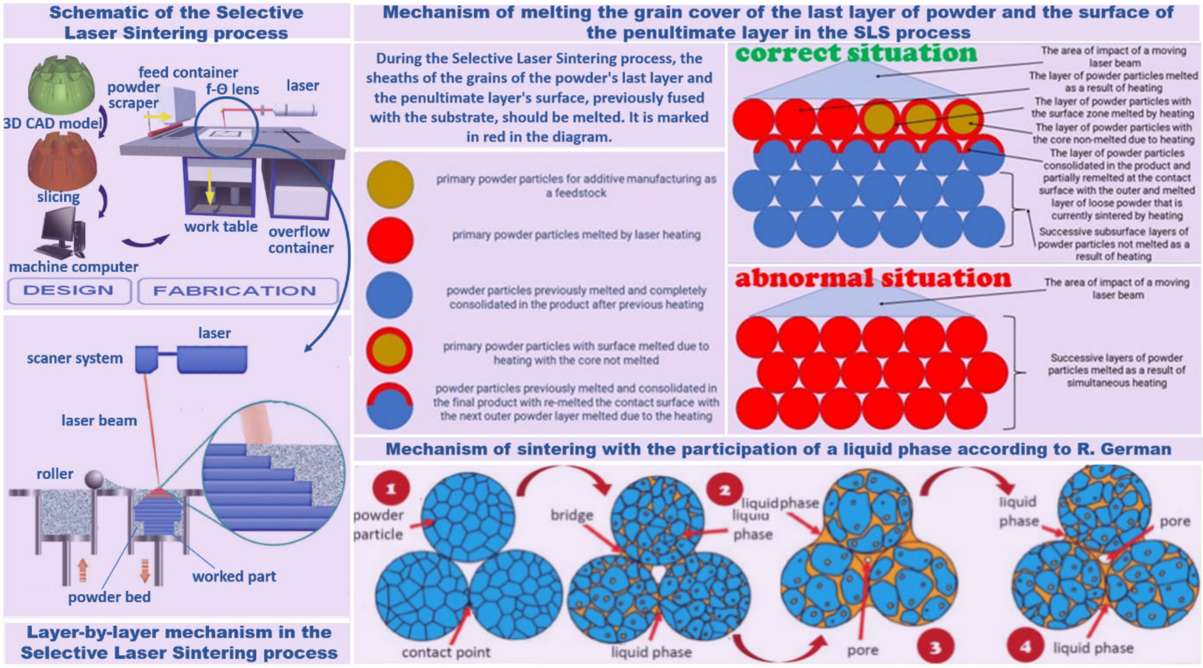


Fig. 27. Original generalised model of selective laser sintering based on epidermal heating of the last layer of powder and only the surface of the previously sintered layer

In the case of Ti6Al4V, the best corrosion resistance is achieved by the selectively laser-sintered alloy under conditions that provide minimal porosity (Fig. 28 left), exhibiting the highest value of polarisation resistance and the lowest value of corrosion current density. The environment in which the material produced in this way obtained the best corrosion resistance was the Tyrod solution, where the highest value of polarisation resistance and the lowest current density were obtained. In addition, it should be noted that in the test in Ringer's solution with the addition of hydrogen peroxide, the value of polarisation resistance decreased by up to 85%. The material produced under conditions providing a porosity of 10.53% has low corrosion resistance.

The results of corrosion tests of the selectively laser-sintered Co25Cr5W5MoSi alloy indicate that in Ringer's solution with the addition of hydrogen peroxide, the value of polarisation resistance decreased several times by 82-90, depending on whether there is a partial overlap of laser paths (the best variant 0 or not) (Fig. 29). The analysis of the results also indicates a significantly higher susceptibility to corrosion damage of the tested materials in a solution with the addition of hydrogen peroxide compared to an acidic solution containing 1% addition of acetic acid, as evidenced by the recorded values of, among others, the free and corrosive potential of the materials. Based on the recorded

Table 1.
Chemical compositions of reagents used in corrosion testing

Solution component	Saline solution (Fusayama's artificial saliva)	Ringer's solution	Tyrod's Solution
NaCl, g/l	0.4	8.6	8.0
KCl, g/l	0.4	0.3	0.2
$NaH_2PO_4 \cdot H_2O$, g/l	0.69	-	0.05
$CaCl_2 \cdot H_2O$, g/l	0.79	0.243	0.2
Urea, g/l	1.0	-	-
Distilled water	1.0	1.0l	1.0
Additional alternative ingredients	-	It can be with the addition of 1% H_2O_2 or with the addition of 1% acetic acid concentrated	-

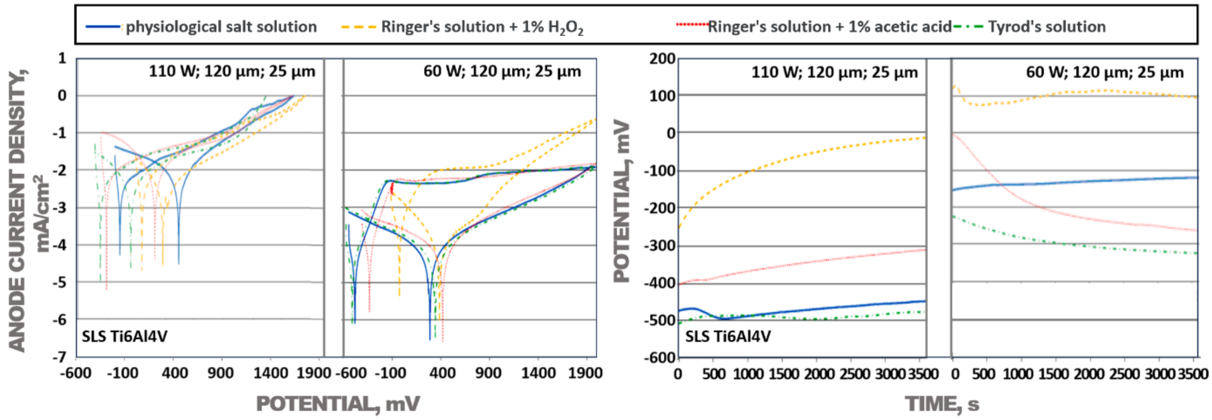


Fig. 28. Curves recorded in a corrosion resistance test of Ti6Al4V alloy produced under conditions providing minimal porosity (left) and porosity of 10.53% (right); 2 drawings on the left anode curves of the potentiodynamic method; 2 figures on the right – changes in the potential of an open circuit over time

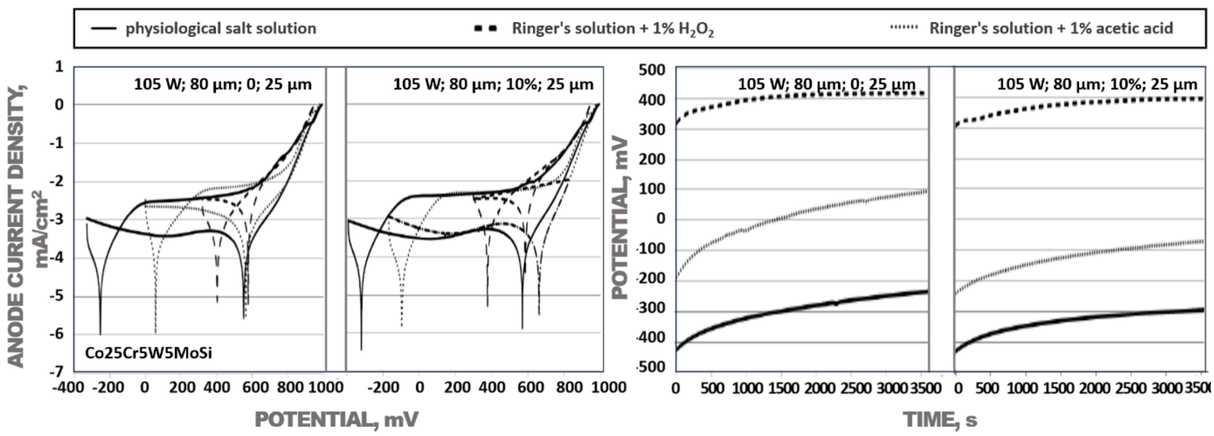


Fig. 29. Curves recorded in the corrosion resistance test of Co25Cr5W5MoSi alloy produced under minimum porosity conditions (right); 2 drawings on the left anode curves of the potentiodynamic method; 2 figures on the right – changes in the potential of an open circuit over time

anode polarisation curves, it can be read that each of the materials, after polarisation above the value of the corrosion potential, passed into a passive state, as evidenced by a straight section of the curve parallel to the ordinate axes in both figures on the left. Comparing the course of the polarisation process of the tested materials, it can be stated that the limit value of current density of 1 mA/cm^2 was recorded at a potential in the range of 0.95 to 0.99 V.

As a result of tribological studies [52] produced by selective laser sintering of Ti6Al4V and Co25Cr5W5MoSi alloys made by the ball-on-disc method with the use of tungsten carbide as a counter specimen, the fundamental influence of even a significant diversity of additive manufacturing conditions (as is the case with the Ti6Al4V alloy) on the wear conditions of the tested materials was not established. As the friction distance increases, the coefficient of friction increases, and in the face of constant load, this is equivalent to an increase in frictional forces. The wear of the Co25Cr5W5MoSi alloy is lower than that of the Ti6Al4V alloy (Fig. 30). The nature of wear and tear is illustrated by scanning electron microscopy images at 5000x magnification.

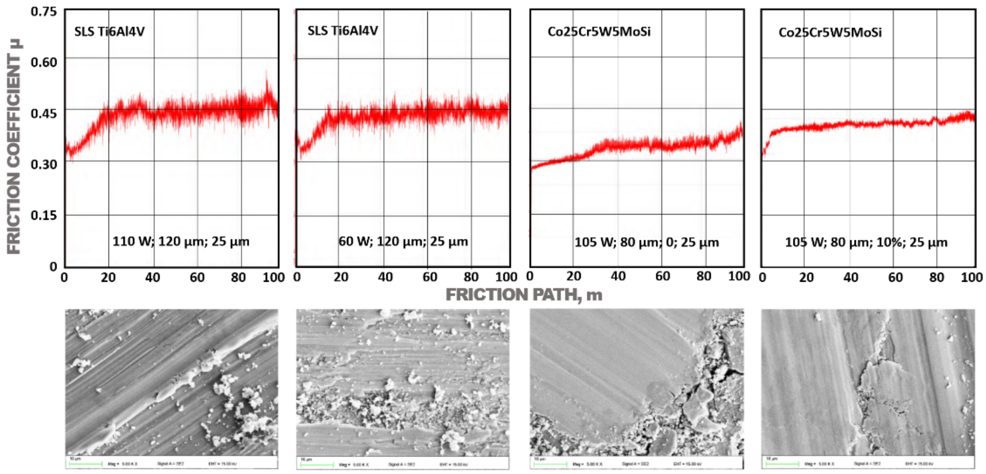


Fig. 30. Wear curves (top row) by ball-on-disc tribological studies using tungsten carbide as counter-specimens produced by selective laser sintering of Ti6Al4V alloys (two columns on the left) under conditions providing minimum porosity (first column) and maximum porosity (second column) and Co25Cr5W5MoSi (two columns right) under conditions providing minimum porosity (fourth column) and end surface structure after the test lasting approx. 690 s (bottom row)

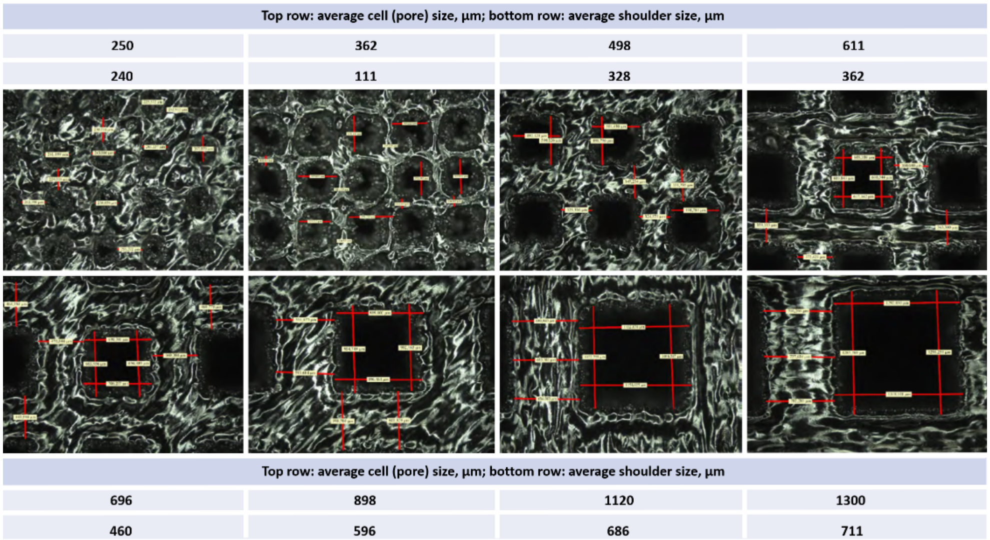


Fig. 31. Examples of various scaffolds with light microscopy measurements to determine the pore size and arms of the scaffolds between them produced by selective laser sintering of Ti6Al4V

6. Investigations of the structure and properties of micro-guided and micro-splined materials made of titanium and its alloy Ti6Al4V and subjected to ALD atomic layers

From the point of view of implant therapies, it is extremely important to ensure the proliferation of living cells, especially osteoblasts, on the surface of implants to create a permanent, high-strength connection between the artificially inserted implant and the natural living cells of the body. The expectation is the basis for the Author's bio-metal materials, covered by the Author's patents [47-50, 60,61] and various awards at international invention fairs [62-66] and the Author's publications. There are two types of solutions for this. On the one hand, these are porous materials with adjustable pore sizes produced by selective laser sintering in scaffolds (Fig. 31).

Extensive experimental studies were carried out to establish the correlation between the conditions of selective laser sintering and the geometrical features of the obtained scaffolds, considering the size of the pores and the arms of the skeleton between them (Fig. 31) [44,45,52]. It is essential for designing the proliferation processes of living cells inside the pores of the scaffolds.

Figure 32 shows the structure of scaffolds produced by selective laser sintering from titanium powder (top row) and Ti6Al4V alloy (bottom row).

Alternatively, dental implants can be constructed in this way [44,45,52], where a several-layer skeletal porous layer of the scaffold, referred to as implant-scaffolds, is applied on a solid core, e.g., in the form of a cylinder or a truncated cone (Fig. 33a). The diagram in Figure 33b indicates the concept of a bio-metal material, with a layer arrangement as shown in Figure 33b, where the proliferation of natural living osteoblast cells imaged in pink occurs inside the pores of the scaffold.

Measurements of the thickness of ALD layers using a spectroscopic ellipsometer in 25 places of each sample indicate that the differences in the thickness of the layers, e.g., TiO_2, do not exceed 2 nm. Their thickness increases from 55.95 nm to 148.73 nm with the increase in the number of ALD cycles from 500 to 1500, which is illustrated, for example, on two-dimensional maps of the distribution of the thickness of the atomic layers (Fig. 34a-d). In the case of layering in 500 cycles, they are uniform. In comparison, in the case of 500 or more ALD cycles, there are clusters of atoms with a diameter of about 1 μm located every few micrometres, while in the case of 1500 cycles, they reach the size of several micrometres in the form of islands of atoms.

Surface layers with a thickness of several dozen to several dozen nanometers have an amorphous structure observed on a crystalline substrate of titanium (Fig. 34e) and Ti6Al4V alloy (Fig. 34f) in a high-resolution transmission electron microscope (HRTEM) (Fig. 34e,f), which was confirmed by electron diffraction studies (Fig. 34g).

It is also possible to use analogous implants used in maxillofacial surgery (Fig. 35) [52] to treat progenia (morphological foremandibone) by extracting the part of the mandibular bone that is overdeveloped concerning the upper jaw.

A second pro-proliferative approach for living cells involves the production of dental implant structures with surface micro protrusions by selective laser sintering (Fig. 36).

Designs of dental implants in the form of scaffolds and implants containing surface micro protrusions allow the use of the original proprietary technology of mounting the implants by inserting/pressing

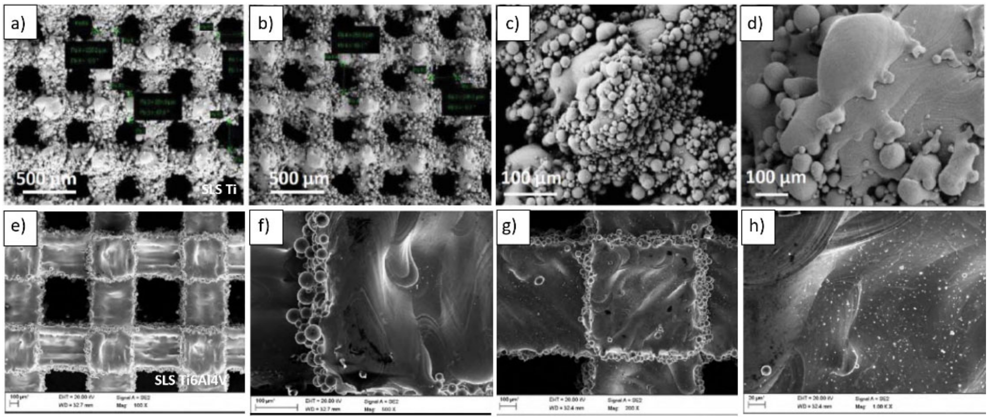


Fig. 32. The porous structure of scaffolds produced by selective laser sintering from titanium powder (top row) and Ti6Al4V alloy (bottom row) – magnification increases from left to right

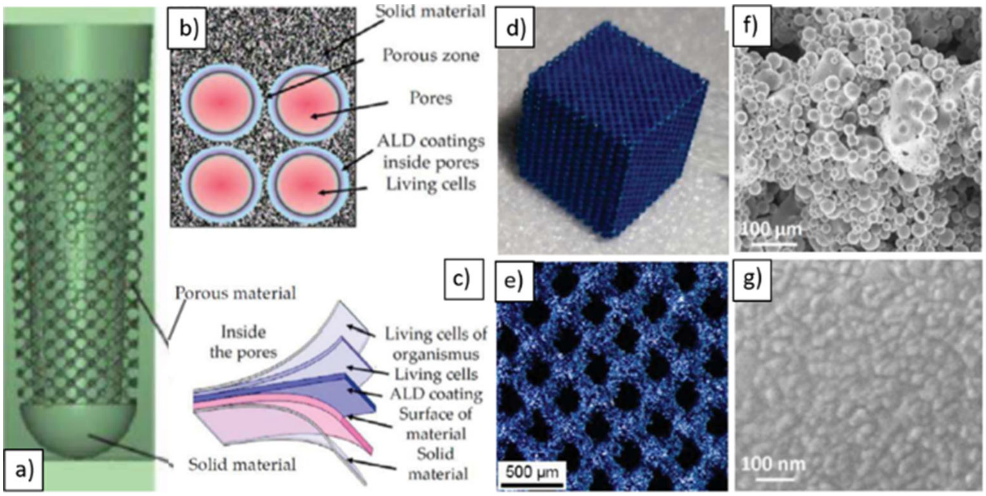


Fig. 33. Diagram of conical dental implants with a solid core and a multi-layer skeletal porous layer defined as implant-scaffold (a) and bio-metal materials (b) with a sequence of layers on the inner surfaces of the pores (c); structure of the porous skeleton of Ti5Al4V in the form of a cube with a side of 10 mm (d), on which atomic layers of TiO_2 were applied in 1000 cycles (e) with a view of the surface of the Al_2O_3 layer after 1500 cycles of ALD on a porous Ti6Al4V substrate (f) and the surface of the TiO_2 layer after 1500 cycles of ALD on a porous Ti substrate (g)

into the socket after the directly extracted tooth, instead of the classic drilling of a hole in the dental process and subsequent screwing in implants containing the appropriate thread. For this purpose, an original proprietary device was developed, which, together with the method of implant assembly, was applied for a patent (Fig. 37) [52,67,68].

It is interesting to provide a guaranteed insertion/insertion force of the implant due to hammering by the dentist on the horizontal tip of the device. Inside the device, there is a suitable fuse that carries only loads lower than critical because of the appropriate selection of plastic properties of the material, which is pushed through an eyelet analogous to that of a drawing in the event of exceeding the force determined as critical, when plastic deformation of this element occurs. The force is not transferred to the actuators of the device so as not to cause any damage in the cavity by overloading the patient's oral health.

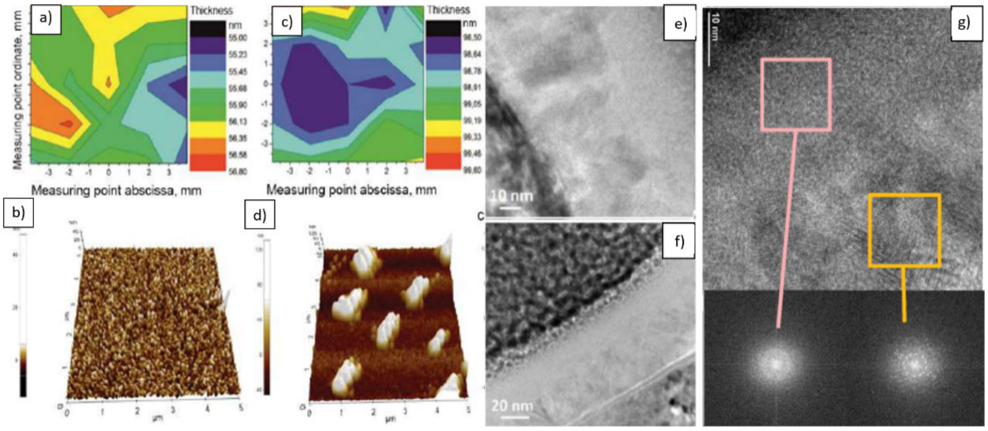


Fig. 34. Maps of the thickness distribution of TiO_2 layers produced by ALD on Ti substrate after 500 (a,b) and 1000 cycles (c,d) and a view of the surface (b,d) and structure of the amorphous TiO_2 coating layer on Ti (e) and Ti6Al4V (f) substrate together with diffraction images of the amorphous coating (pink) and crystalline Ti (orange) substrate (g)

The purpose of structural changes in both implants and implant scaffolds resulting from the stress analysis using the finite element method (FEM), and mainly from clinical practice, is slightly different concerning the method of fixing crowns on the base of implants or implant scaffolds [68]. It turns out that critical stresses occur in the fixing screw, occurring in typical solutions available on the market, where, under certain unspecified conditions, patients lead to exceeding the permissible strength of these screws and disintegrating such a type of prosthetic restoration. The Author's solution to the problem, covered by the Author's patent, is a conical connection between the implant and the crown, in which much higher loads are allowed, practically eliminating the causes of the aforementioned damage to the prosthetic restoration (Fig. 38).

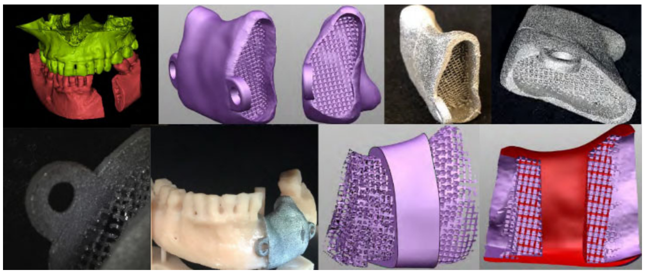


Fig. 35. Diagram of virtual design of extraction of mandibular parts as a result of neoplastic lesions and virtual designs of necessary connecting implants (in purple) and examples of implants produced by selective laser sintering (grey) and an example of application on a polymer model produced by the SLA method; The last diagram indicates the production of biological-metal material, where the purple tissues are natural, and the metal fragments are red along with the scaffold

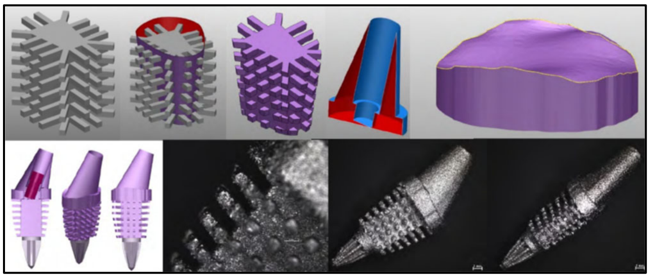


Fig. 36. Examples of dental implant design solutions with protrusions, along with examples of implants produced by selective laser sintering (last three photos)

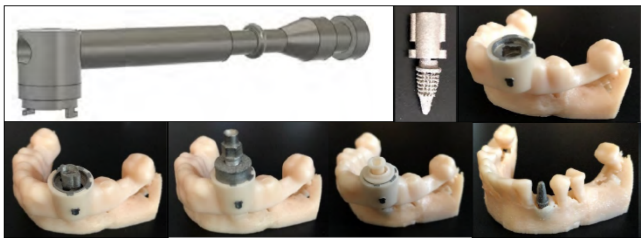


Fig. 37. Diagram of the device for pressing/inserting dental implants and implant-scaffolds suits and the sequence of assembly steps

7. Evaluation of biological properties of micro coated and micro splined materials made of titanium and its Ti6Al4V alloy and atomic layered ALD

Implant-scaffolds, implants with protrusions, and solid implants were subjected to a series of biological tests [44, 45,52] to determine the possibility of live cell proliferation and exclude toxic effects.

It has been shown that live osteoblast cells proliferate on all tested media (Fig. 39), but in the case of Ti6Al4V medium, in each case, it is better than in the case of a control sample from laboratory glass. It turns out that covering the surface with a multilayer ALD coating with Al_2O_3 causes the most beneficial effects in this respect, which confirms the advisability of applying surface layers using the ALD method on implants and implant-scaffolds to improve the conditions for the proliferation of living cells.

The influence of the surface structure of the Ti6Al4V alloy on biological behaviour was investigated. To investigate cytotoxicity, cells in the logarithmic growth phase were cultured with SAOS-2 Cell Line Human in direct contact with the test material at 37°C in an atmosphere of 5% CO_2. 24 hours before the end of incubation, a positive control (PC) was performed – Triton X-100 at a final concentration of 0.01%. Cells grown in a full-growth medium on a culture plate were used as a negative control (NC). After 72 hours, the XTT assay was performed, which consisted of cleavage of the yellow tetrazolium salt XTT (sodium salt 2,3-bis [2-methoxy-4-nitro-5-sulfophenyl]-2H-tetrazolio-5-carboxyanilide), which is converted into a product soluble in an aqueous medium, and the reduction process occurs mainly on the cell surface or in the plasma membrane with the participation of the transmembrane electron transport chain. It was found out that the cells' metabolic activity (survival) is complete in the case of solid surface and slightly reduced in the case of scaffolds and surface projections (Fig. 40).

An analogous cell culture was performed to determine the degree of genotoxicity through a micronucleus assay. After 24 hours, the conditioned medium was replaced with extracts by administering 100 µl of extract per well. After 48

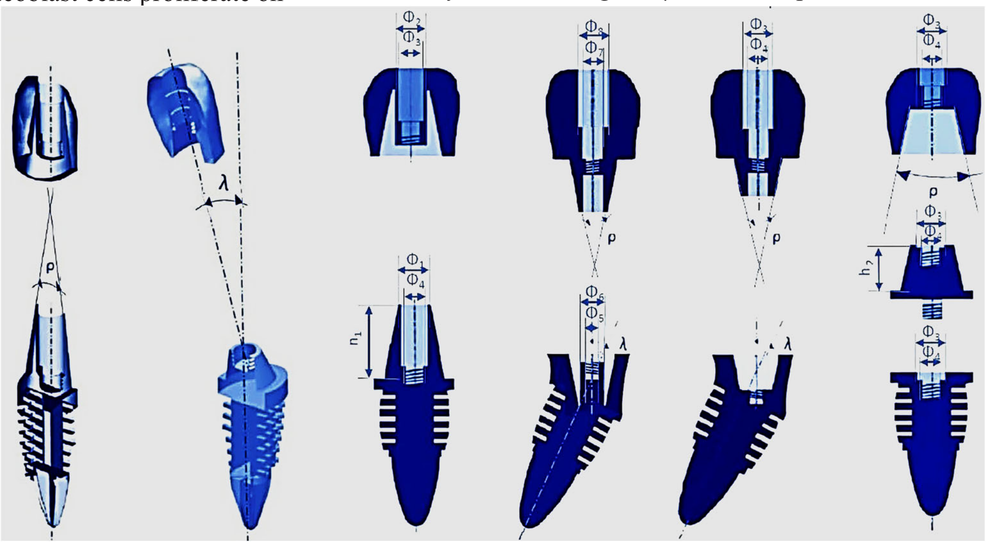


Fig. 38. Examples of design solutions for the method of fixing crowns are based on implants or implant scaffolds with a conical connection between the implant and the crown

Skeleton material	Coatings	% viability = absorbance of test samples * 100%/ absorbance of control specimens % life (average of 8 determinations of formazan solutions taken in Dimethylosulfoxide DMSO)	Result
% life		85 90 95 100	Result
Controlling specimen			96,4
Ti	-		88,9
	TiO_2		92,7
	Al_2O_3		90,9
	HA		97,6
Ti6Al4V	-		97,0
	Al_2O_3		100,2
	HA		97,2

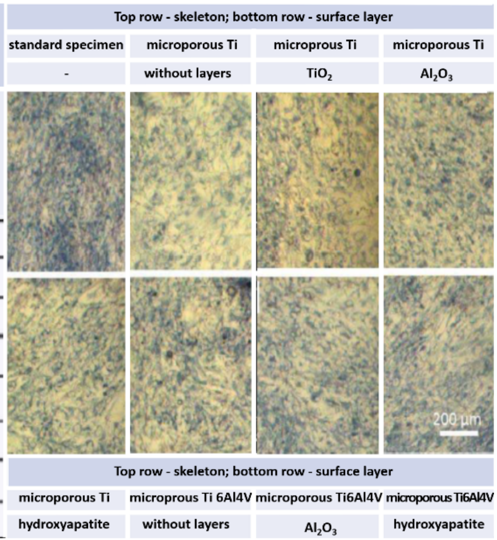


Fig. 39. Dependence of viability of viable osteoblast cells from the hFOB 1.19 experimental line (Human ATCC-CRL-11372) on the type of material and surface layers used, along with a review of the view of cultured osteoblast cells

hours, cytochalasin B was administered at a terminal concentration of 3 μg/ml to inhibit cytokinesis. Mitomycin C at a concentration of 1 μg/ml was used as a positive control (PC). After incubation, the cell monolayer was washed with a saline solution and fixed with a 3.7% formaldehyde solution for 20 minutes at room temperature. Then, the fixed cells were washed with saline. Then, the fluorescent tracer Hoechst 33342 was added at a final concentration of 5 μg/ml to stain the DNA of the cell nuclei and micronuclei. The results presented as % of micronuclei in binuclear cells indicate that the surface structure of the selectively laser-sintered Ti6Al4V alloy is of little importance from this point of view (Fig. 40).

Cell culture with SAOS-2 Cell Line Human was performed in the same way as before to assess the proliferation and cytotoxicity of the tested material by LIVE/DEAD labelling based on fluorescence techniques using two probes distinguishing between cell viability parameters, i.e., intracellular esterase activity and cell membrane integrity. The probes are fluorophores: calcine acetoxymethyl ester (calcine-AM) staining the cytoplasm of living cells green (ex/em 495/515 nm) and ethidium homodimer staining dead cells red, passing through the damaged cell membrane and attaching to nucleic acids (ex/em 495/635 nm), and additionally, Hoechst 33342 tag was used for labelling cell nuclei. After incubation, the cells were gently rinsed with PBS and stained for 15 minutes in the dark with the dyes for fluorescence microscopy. Figure 40 in the last column shows the results of these studies, which are most beneficial due to the proliferation of cells on a flat surface.

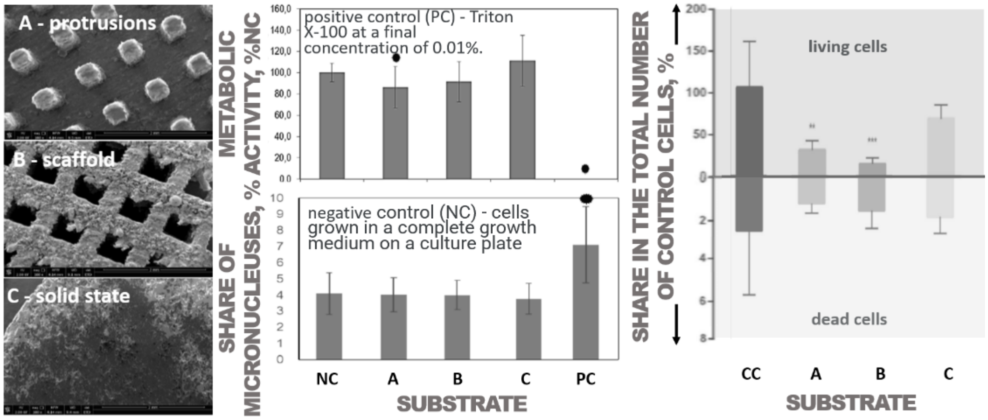


Fig. 40. Structure of the medium for the culture of live SAOS-2 cells as the surface of Ti6Al4V alloy specimens observed in scanning microscopy (column on the left); above metabolic activity (survival) of SAOS-2 cells after 72 h of incubation with the tested materials (* \u2012 statistical significance against the negative control (NC) 24 h for p<0.05) and below the assessment of genotoxicity of the tested specimens after 72 h of incubation with the tested materials (* \u2012 significance against NC- for p<0.0001) (middle column); the number of SAOS-2 cells alive (top) and dead (bottom), respectively, on the test surfaces presented as % of the total number of control cells; Statistically significant results for **p<0.01 and ***p<0.001 relative to controls

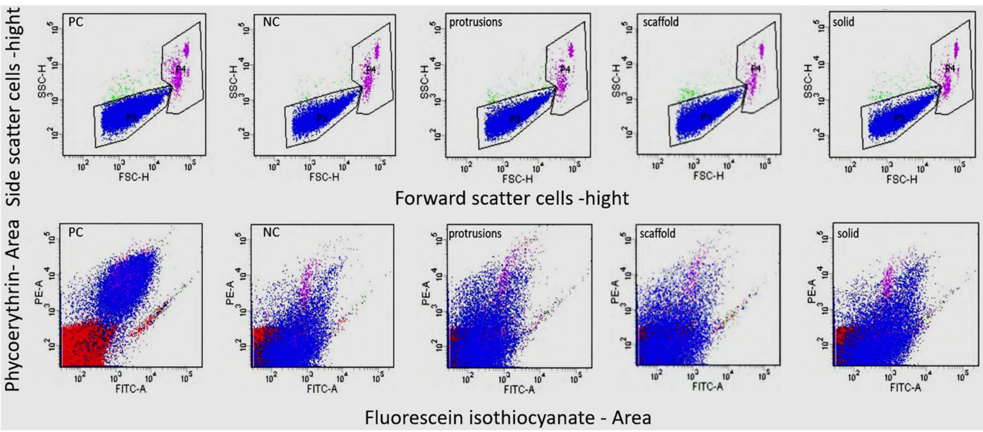


Fig. 41. Assessment of spontaneous platelet aggregation after contact with the test materials – in the upper row, there are flow cytometer images; areas marked as P3 – single platelets are normal, single platelets, and areas marked as P4 – aggregates; The bottom row shows the dot graphs of platelet activation

The study of platelet activation and spontaneous aggregation by flow cytometry was performed to assess the significance of contact with material with different surfaces. The experiment also used a negative control (NC), which was whole citrate blood, and a positive control (PC), which was whole citrate blood activated with adenosine-5′-triphosphate (ADP). Whole citrate blood was incubated for one hour with test specimens, then diluted 10-fold and labelled with three antibodies:

1. CD61 coupled with the PerCP probe recognizing this marker on the platelet surface (glycoprotein with a molecular weight of 110kDa, gpIIIa – a subunit of the β integrin gpIIb/IIIa),

2. CD62 labelled with phycoerythrin (PE) recognizing this receptor (P-selectin),
3. FITC-labelled PAC-1 binds to the active fibrinogen receptor (GPIIb/IIIa).

CD62 and PAC-1 antibodies are markers of platelet activation. Antibody labelling was performed for 20 min at room temperature in the dark. The blood specimens were then fixed with the CellFix reagent. The specimens prepared this way were analysed on the Accuri BD flow cytometer and FACS ARIA (Becton Dickinson). Based on the analysis of laser light scattered forward (FSC – Forward Scatter) and lateral (SSC – Side Scatter), populations of single platelets and platelets in the form of aggregates were determined. Platelets were identified by a fluorescent signal from a PerCP fluorochrome coupled to a CD61 antibody.

The level of platelet aggregation by the sample material with a smooth surface is at the level of the negative control and shows the lowest thrombogenicity among the tested materials. For the spike and scaffold specimens, an increase in aggregation of about 25% was observed compared to the negative control.

The fluorescent signal from platelet activation markers for both the active form of the fibrinogen receptor and P-selectin in blood incubated with the test material with a smooth surface is more than 50% higher than the negative control, meaning the surface strongly activates platelets. The materials of the specimens with spikes and scaffolds for the marker of the active form of fibrinogen emit a signal at the negative control level. On the other hand, the scaffold material activates platelets very strongly for the Selective P marker. The results of the studies are illustrated in Figure 41.

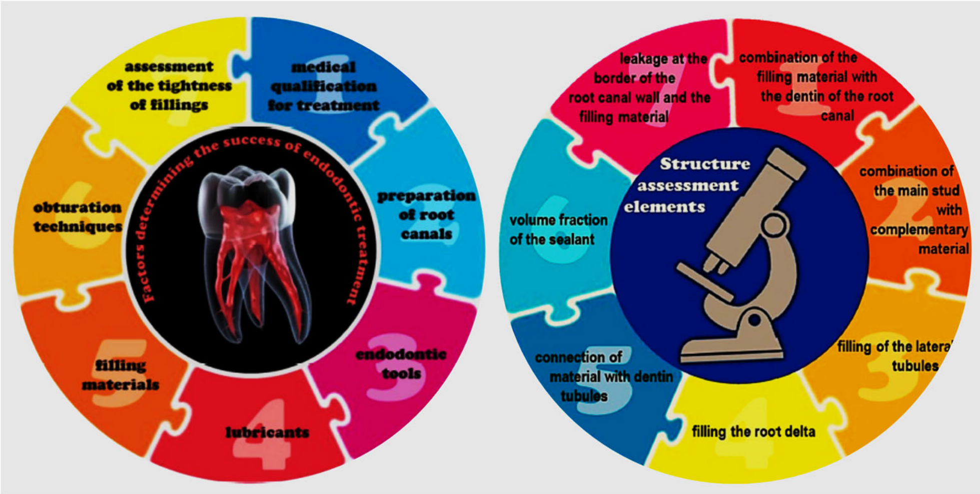


Fig. 42. Diagram of the factors determining the success of endodontic treatment (left) and criteria for the evaluation of the research material depending on the variants of development and obturation of the root canal (right)

8. Studies of prosthetic fillings used in endodontic treatment of caries

A very wide range of the Author's research [53-56], using methods and tools of materials engineering, includes selecting filling materials and technologies to prepare root canals and obstructions. A wide range of methods were used for the analysis, not only in materials science and production engineering but also in management, knowledge engineering, and technological foresight. It is an original approach, but it requires a consistent analysis of the impact of all the factors determining the success of endodontic treatment, which are presented in Figure 42 (left). Figure 42 (right) presents the criteria for evaluating the test material depending on root canal development and obstruction variants.

Important factors that determine the correctness of endodontic treatment include the preparation of the root canal, the experience of the dentist, the related obstruction technique, and the selection of tools. Endodontic treatment is based on the optimal use of the filling material, ensuring the best possible sealing of the root canal with the appropriate and required shape after removing the contents contained in it and after its thorough disinfection. As experiments have shown, the goal of endodontics is to "asymptotic" and hypothetically produce a monoblock as a solid, bound, continuous filling material from one root canal wall to another, usually mechanically forming a homogeneous unit with root dentin. A strong connection between the monoblock components and the reinforcing material is required, and the modulus of elasticity of the monoblock and this material should have similar values. The concept of monobloc is only a model adopted in the literature and is not fully confirmed in clinical practice. The basic monoblock type exhibits a single interface between the material and the root canal wall, as in the case of Hydron, MTA mineral trioxide aggregate, bio-gutta, and polyethylene fibre core. The secondary monoblock has two points of contact, between the core material and the cement and the other between the cement and the dentin, as in the case of gutta-percha-based fillers due to the presence of sealant and adhesives as substitutes for gutta-percha, as well as resilon with methacrylate-based sealant. Tertiary monoblocks have a third boundary between the filler material and the bonding medium, such as EndoRez or gutta-percha coated with CLEARFIL LINER BOND 2V or ActiV GP resin.

Detailed results of studies conducted on 80 human teeth removed for medical indications but not affected by caries were divided into five groups of 16 teeth. After the root canals were prepared, the examined teeth were filled with material based on gutta-percha (three groups) and resilon (two groups) using various methods, including the use of thermoplastic thermohydraulic condensation technique using a Buchanan plug (SybronEndo) and the Obtura III system (SybronEndo) fixed at 160°C. After filling with the filling material, the teeth were incised with a diamond disc on one side along the root, to a depth of 1 mm, using a prosthetic handpiece. After immersion in liquid nitrogen, a longitudinal crack was made. Each sample was sputtered with a thin layer of gold to prepare for materialographic studies in a scanning electron microscope. To assess the tightness of the root canal filling with gutta-percha and resilon-based materials, attention was paid to seven elements of the evaluation of the test material depending on the preparation and obstruction of the root canal. An analysis of the weighted scoring method was carried out along with the development of a meteorological matrix of contextual attractiveness, which showed that among the methods of assessing the tightness of root canal fillings, the highest values and a clear advantage over other methods in terms of effectiveness were obtained by visualisation methods with the use of materialographic microscopes. Therefore, extensive materialographic studies were performed, among others with the use of scanning electron microscopy. Examples of test results for both of these materials, in the case of ensuring the required tightness (top row), as well as in the case of defects consisting in the occurrence of undesirable gaps (bottom row), are presented in Figure 43, based on which it is possible to optimise the conditions of root canal obstruction in endodontic treatment.

To analyse the usefulness of the filling materials, the digital twin method was used as an approach appropriate for Industry 4.0 and the resulting idea of Dentistry 4.0 by conducting experiments in virtual space and theoretical analysis using methods usually used in management sciences, especially in foresight research within knowledge management, using portfolio methods, drawing on the prototype developed by Boston Consulting Group (BCG). The virtual analysis uses, among others, the methodology of procedural benchmarking and comparative analysis with contextual matrices as tools often used by the Author's team to evaluate surface engineering technologies and other dental issues. Criteria for multi-criteria assessment of generalised indicators characterising the potential and attractiveness of root canal filling materials have been determined. Each criterion was assigned weights reflecting their importance; each set of criteria was summed up to one, and then the methods were evaluated according to the pre-adopted criteria on an appropriately selected scale, using expert knowledge. A ten-point unipolar positive interval scale without zero was used, where 10 is the maximum possible rating, and 1 is the

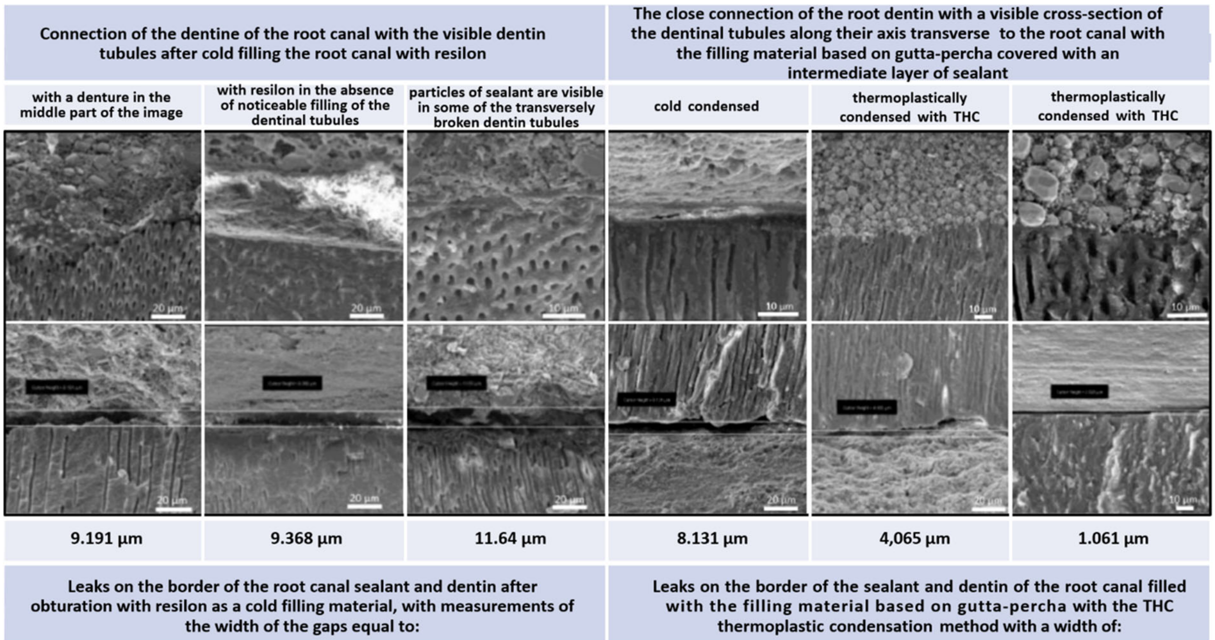


Fig. 43. Exemplary results of scanning electron microscopy (SEM) studies of the connection of root canal dentin with visible dentinal tubules after cold filling of the root canal with resilion (left) and close connection of root dentin with a visible cross-section of dentinal tubules along their transverse axis to the root canal with gutta-perch-based filling material covered with an intermediate layer of sealant (right) with measurements of the gap width in where they have been identified (bottom row)

minimum grade. The numerical score for each root canal filling material under each criterion shall be multiplied by its weight. Then the individual subscores for each set of criteria are added together to obtain a weighted average as a tool for comparative analysis. The results of the analysis are presented in Figure 44 (on the left) in the form of a dendrological matrix divided into four quadrants, where the best position is guaranteed by wide stretching oak, in which the materials for polyesters, gutta-percha, on synthetic resins and silicones are located. In contrast, the weakest position is provided by quaking aspen.

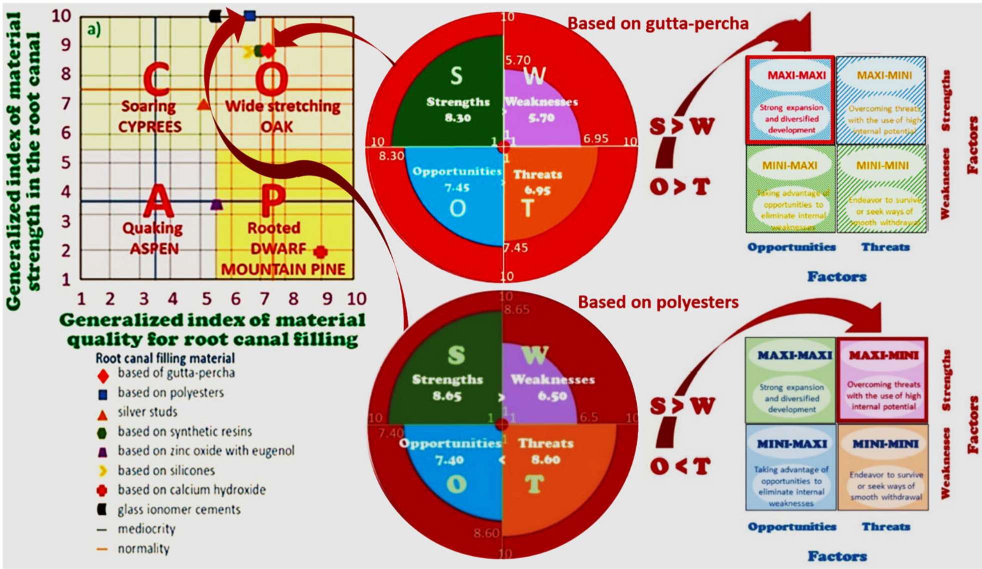


Fig. 44. The results of the dendrological analysis of the analysed filling materials (left) and the results of the SWOT analysis (middle) of gutta-percha (top) and polyesters-based filling materials (so-called resilon) with an indication of the recommended development strategy (right)

The results of the analysis showed that no filling materials meet all the requirements, demonstrating that only two filling materials, gutta-percha-based material and resilon, are of real practical importance. The gutta-percha-based material achieved a high rating in terms of strength and a relatively high level of fill quality, in contrast to resilon, which has a comparable strength index but loses out on quality rating.

A SWOT (Strengths-Weaknesses-Opportunities-Threats) point analysis was also performed as a method of integrated identification and comparison of the strengths and weaknesses of each of this gutta-percha and resilon filling materials, as well as the opportunities and threats that flow from the environment to them. Each time each filler material was compared, five key internal and external SWOT factors were identified, with weights reflecting their importance. The universal scale of relative states described earlier was used. Based on each of the criteria factors, the compared materials were evaluated, multiplying the expert score by the weight assigned to each criterion. This way, the sum of the weighted results for each group of SWOT factors for each filler material was obtained (Fig. 44 in the middle). The evaluation criteria adopted consider the specificity of the compared filling materials, and the weights assigned to them are not identical in each of the analysed cases. Therefore, the results of the analyses cannot be compared directly and uncritically. In the case of obstruction using gutta-percha-based material, a multi-criteria SWOT analysis indicates that strengths are rated as (8.30) and (8.65) for filling with resilon. The weakness rating is (5.70) for gutta-percha-based filling, while for resilon, the value is (6.80). When using a gutta-percha-based filling material, the odds were (7.45), while when using resilon, the odds were (7.40). The hazards associated with using gutta-percha-based material are (6.95), while the environmental hazards associated with resilon correspond to the assessment (8.60).

The matrix of possible development strategies for each material may be the only platform to compare the development prospects of these two filler materials (Fig. 44 on the right). For gutta-percha-based material, the weaknesses are much smaller than the strengths of this S > W filler material, and at the same time, the risks are slightly less than the O > T chances. The predominance of positive factors, both internal and external, points to the requirement for full exploitation and the resulting diversification of the market combined with strong market expansion. The search for new customer groups and new markets is highly desirable. Such a strategy is referred to as aggressive MAXI-MAXI.

In the case of resilon, the strengths have a significant advantage over its weaknesses S > W. At the same time, the chances are much lower than the threats from the environment O < T. Therefore, it is only possible to apply the conservative development strategy of MAXI-MINI, which requires overcoming significant environmental risks, with the necessary use of the significant potential of this filling material, which can lead to spectacular failures, although unexpected success is also possible.

Such an analysis does not indicate the actual competitiveness of resilon with the gutta-percha-based material, which deservedly maintains a strong position as the gold standard of endodontics whereby the tight bond of the filling material is uniformly covered by an intermediate layer of sealant and the dentin of the root canal is only bonded in the case of thermal filling with THC filling material using Obtura III and System B devices.

9. Application of the Dentistry 4.0 concept for the optimal design and manufacture of implant-based prosthetic restorations manufactured with additive technologies

The design of an optimal prosthetic restoration should begin at the stage of the patient's consultation visit to the dentist, during which a tomogram should always be performed on the cone beam computer tomography CBCT device to guarantee the highest available resolution of X-ray images guaranteeing the correct reproduction of the smallest structures, especially, in bone tissues and dental tissues of the patient. To carry out proper diagnostics before starting the treatment of reconstructing the patient's lost teeth, it is very important to determine the course of the nerve canals correctly, correctly qualify the teeth for conservative, endodontic, and prosthetic treatment, or to decide to extract them. Only high-resolution CBCT devices allow us to achieve the appropriate quality of preliminary information in today's dentistry. In addition, such technology now makes it possible to effectively generate a digital twin of the patient's teeth and bone base. The technology also has a significant limitation. It is a relatively inaccurate representation of soft tissues. Despite the use of many filters and the development of the technology, the information is still insufficient to produce a prosthetic restoration that meets the highest expectations of soft tissue fit. Therefore, it was necessary to develop an effective protocol for transferring information from the patient's oral cavity, obtained because of an intraoral scan or an impression scan made with an impression mass, and transferring this accurate model to a digital twin model, which will also include a model of the bone base. For this purpose, a method of designing and manufacturing positioning plates manufactured in SLA technology with geometric markers was developed. The plate and the markers are visible on the CBCT tomogram, making it possible to position the bone base and the intraoral model using a typical positioning method, e.g., three or five points. Using the automatic positioning function available in many CAD programs is not recommended, as it usually introduces a slight deviation, disqualifying such a model from further design procedures. Creating an appropriate 3D digital model of these tissues provides information about the extent of soft tissues in the oral cavity and the bone base underneath the tissues.

After making a digital twin imaging of soft and bone tissues in the patient's oral cavity, it is possible to start planning the placement of implants to maximise the use of the bone base and minimise the need for additional bone regeneration procedures. In the Author's practice, it was assumed that it is appropriate to use the patient's bone base primarily to minimise the risk of resorption of the bone base produced as a result of bone regeneration, both through bone regeneration procedures with bone substitute material and through grafts of bone blocks in the long term of use. Such an approach minimises the risk of complications over a longer period of use, which is particularly important in patients with difficult implantation conditions.

According to the Author's concept, it is possible to reconstruct the dental arch correctly based on two solutions. To reconstruct the entire dental arch, it is possible to use only

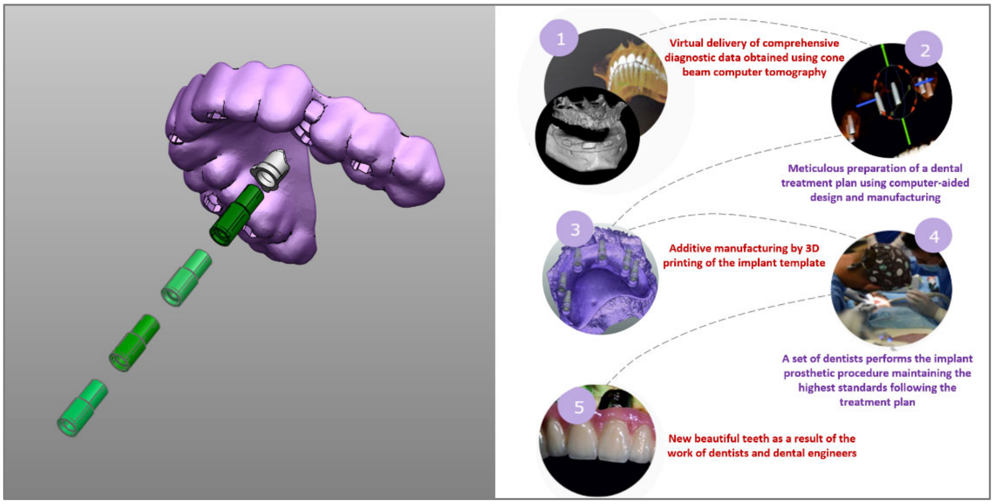


Fig. 45. Diagram of the implant template according to the Author's concept, including from the top the template plate made in the additive SLA 3D printing technology with the use of a dedicated resin, an individual titanium sleeve manufactured additively using the SLS method, and 4 drill overlays made with the additive SLA 3D printing technology (all elements can be sterilised while maintaining the original shape) (on the left) and an organisational chart of the protocol for the design and implantation procedure according to Author's concept (right)

two implants in the case of the lower arch and three implants in the case of the upper arch. The optimal solution, widely used in the Author's practice, is four implants in both the lower and upper arch. After obtaining information related to the scope of treatment from the patient and the main dentist conducting the treatment, the dental engineer develops an optimal initial treatment plan in terms of the transmitted forces, which the dentist verifies, and then, after its approval by the patient, an implant guide is designed and manufactured.

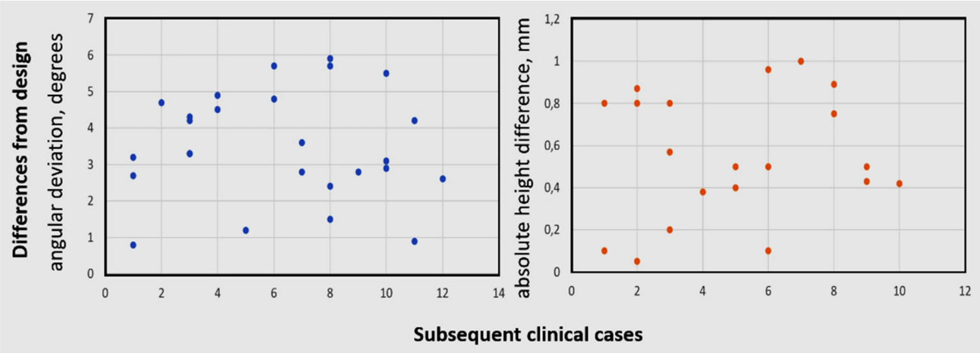


Fig. 46. Examples of verification of the mapping of implant placement in the bone base concerning the design: angular deviation (left) and absolute height difference (right)

The implant guide is manufactured using additive 3D printing technology (Fig. 45). Two materials are used. The first is a resin cured in the stereolithography SLA technology, from which the implant template plate is created. The element is responsible for correctly positioning the template about the soft tissues so that its position is unambiguous. Due to the very good shape reproduction concerning the design, no additional pins attaching to the bone base are used. It is consistent with the concept of minimally invasive surgery. Despite the lack of permanent fixation of the template, it is possible to achieve very high repeatability of implant placement. The guide sleeves are made of titanium alloys using additive 3D printing technology. They are always components manufactured individually for a specific clinical situation and used only once. Such an element is based on a bone base, which improves the stabilisation of the template. Even with edentulism, it is possible to carry out the implantation successfully without additional fixing pins. The last element of the system is drills for drilling bones, which are individually designed and manufactured in additive technology, stereolithography, and SLA 3D printing; spacers are mounted, which enable very precise guidance of the drill concerning the template. The technological clearance between the guide sleeve and the drill pad is approx. 0.005 mm, thanks to which the drill guide by the dentist performing the implantation procedure is accurate, and at the same time, the sleeve allows the use of an implant motor with torque measurement, as no friction is generated between the system components. A minimum of 3 drills should be used before the implant bed is prepared. The first drill is a pilot drill that allows you to verify the design assumptions in practice. The second and third drills allow you to widen the hole so that its diameter is approximately 0.5 mm smaller than the diameter of the implant. Standard drills from the implant cassette of the implant system are then used to develop the implant bed. The implant itself may (but does not have to) be inserted using a template. The Author's observations confirm that the mapping of the implant placement concerning the design is within the assumed framework. Such a protocol allows the bone to be kept cool during implant insertion. In addition, the operator can perform this procedure under visual control, minimising the risk of error.

In Figure 46, examples of verification of the mapping of implant placement in the bone base concerning the design are presented in patients in two types of surgery: in the case of complete edentulism of the upper and lower arch and the case of reconstruction of the missing pterygoid and single arches. The results refer to implant procedures based on implant templates made according to the Author's abovementioned concept.

Based on the results provided, it was confirmed that the applied protocol based on proprietary implant templates allows the maintenance of a very accurate representation of the position of the implants concerning the design. In the case of edentulism of both the upper and lower arches, it is possible to maintain a very high consistency of the mapping of parallelism to each other of the implants, both in the case of simultaneous implantation of 2, 4, or 6 implants. It confirms that there is no need to use template mounting pins to ensure the required implantation conditions. In the case of guides attached to the patient's teeth around or next to the implant site, the reproducibility of implant placement is even greater. This is because the template is completely stabilised and prevents its sideways movements. Of course, it is possible to raise the template during the individual phases of the procedure. Still, in the end, the drill goes in one direction, and the overlays on the drill limit its movement, so the mapping is correct.

10. Development of a methodology for the application of prosthetic restorations designed and based on implant guides manufactured with the use of additive technologies

Using additive 3D printing technologies allows for a radical change in how prosthetic elements are designed and manufactured. In particular, it is possible to quickly and relatively inexpensively produce extensive structural elements such as prosthetic bases, circular bridge bases, individual beams, and telescopic crowns with full shape reproduction concerning the design. In addition, the wide use of titanium alloys allows for a radical reduction in the weight of such a restoration. The reduction occurs concerning cast components manufactured from CoCr alloys, including usually Co25Cr5W5MoSi. A similar situation occurs in the case of milled parts in a CNC centre. It is worth noting that prosthetic bases have very complicated, irregular shapes, which require the use of tools with a diameter of 1-3 mm, which leads to the occurrence of many technological problems related to the correct reproduction of the shape, e.g., between crowns, precise elements connecting with implants or others. The use of the additive 3D printing technology Selective Laser Sintering/Selective Laser Melting SLS/SLM allows for a significant improvement of these properties because it is possible to reduce non-milled areas, which, according to the Author's analysis, cause an increase in the weight of the manufactured elements by up to 25-30% compared to the element that is the basis of the prosthetic restoration produced by the additive 3D printing method with the same design features. In addition, the use of titanium alloys instead of CoCr alloys, including the usual Co25Cr5W5MoSi, makes it possible to reduce the weight of the prosthetic component by 50% due to the difference in density of the two materials.

During his professional practice, the Author has developed the following division of applied prosthetic works (Tab. 2), illustrated in Figure 47.

The arrangement of implants with the procedure of designing the procedure and prosthetic restoration following the protocol developed by the Author allows for reducing the number of points necessary for effective treatment. The

Table 2.
Practical classification of prosthetic works used in dentistry

No.	Condition of the bone base	Mounting type	Type of prosthetic restoration
1.	In the case of a rudimentary bone base with significant bone atrophy of the mandibular branch, which disqualifies the insertion of implants in the lateral segments, a solution based on two implants with an individual titanium beam and a prosthesis veneered with acrylic reinforced with a titanium base is used	-	-
2.	In the case of a medium bone base that prevents the placement of implants behind the inferior alveolar nerve foramen, a solution based on four implants is introduced and inserted in places 44, 42, 32, 34 in two types	Individual titanium beam on four implants with a prosthesis replaced with a titanium base veneered with acrylic	-
		Four telescopic crowns for fixing prosthetic restorations	Acrylic veneered prosthesis with a titanium base and four secondary telescopic crowns made of bonded composite material
			Titanium bridge veneered with ceramic-composite material veneered with porcelain
3.	In the case of a good bone base, it is possible to use fixed, screwed, non-pull-out restorations	-	A monobridge based on six implants optimally inserted in places 46, 44, 42, 32, 34, 36. It is a porcelain-faced bridge on a Co25Cr5W5MoSi alloy base with integrated individual abutments screwed directly from the implant level

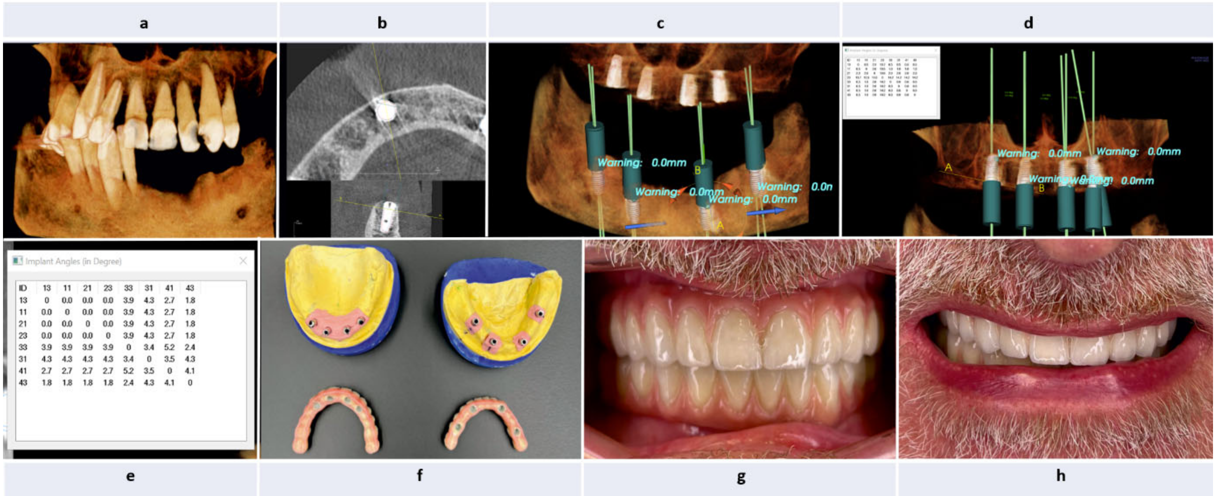


Fig. 47. The sequence of implementation of the treatment plan consisting of reconstruction of the entire dentition based on four upper arch implants and four lower arch implants in a patient with periodontal disease, where a titanium hygienic bridge was used a) view of the initial state – -teeth in the 3rd degree of loosening qualified for extraction, b) view of one of the implants on the cross-section, c, d) a view of the implants planned to be placed together with their planned location, e) a table showing the deviations of the implants from the design in degrees, f) a view of the finished prosthetic work on the model just before assembly, g, h) view of the finished prosthetic work in the correct up/down relation

limitation of the support points results in practical limitations related to properly cleaning the space between the prosthetic restoration and the soft tissues because, in such works, the spaces between the abutments often contain 3 or 4 teeth in the span. For this reason, a solution referred to as a titanium hygienic bridge was developed. A mount based on telescopic crowns was used. Other elements of the prosthetic restoration are typical. Because the work is dedicated to people with bruxism, it is veneered with a composite ceramic material. To reduce the weight of the entire restoration, a substructure produced by the additive 3D printing method using the Selective Laser Sintering/Selective Laser Melting SLS/SLM technology was used. Such a solution has a technological limitation consisting of the inability to veneer this substructure directly with porcelain, as it is impossible to maintain the colour of the restoration over a long period of use. The Author and his team researched and developed a solution enabling veneering works on a titanium alloy base. Such a solution would have many desirable and currently unavailable features, such as low weight, greater strength, the ability to create colour freely, and reduced cross-sections necessary to ensure strength. The works have now gone beyond the scope of conceptual work at the level of 3-6 TRL. The use of ALD atomic layer deposition layers is being considered, which also supports the adhesion of soft tissues to the substructure in the cervical zone, where the veneering zone is located. Related biological problems are discussed in one of the earlier parts of the monograph.

It is extremely important to use implant guides to perform effective implant treatment in cases where the anatomy of the teeth adjacent to the implanted zone is atypical. In particular, it is necessary to plan implant prosthetic treatment using a CBCT CT scan, which will allow us to determine detailed initial conditions before starting treatment. In addition, tool entry paths may be unusual and non-obvious (Fig. 48). Although the cases presented below concern only single implants, the level of difficulty of performing this type of procedure without the use of a template disqualifies the performance of such a treatment plan without the use of an implant guide.

11. Application of digital design methodology for dental implant procedures with immediate implant loading

In everyday practice, immediate implant loads are used when the patient expects an immediate effect in the form of a temporary prosthetic restoration with correct, effective fixation immediately after the procedure. Often, in such a case, the patient also resigns from treating his or her rudimentary dentition and decides on implant treatment with tooth extraction. In the Author's opinion, using the patient's teeth as the basis for prosthetic reconstruction seems reasonable as such treatment guarantees long maintenance of prosthetic work. It is reasonable to use all available prosthetic options before deciding to start implant treatment.

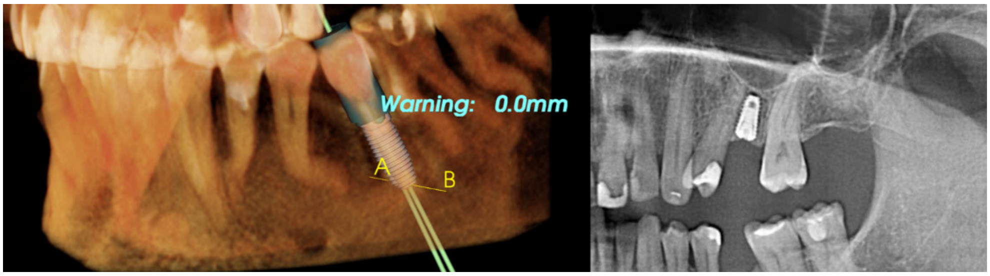


Fig. 48. View of the implanted implant in the CBCT image along with the original design bypassing the adjacent tooth with extremely unusual apex anatomy (left) and the view in the OPG image of the implanted implant along the tilted adjacent tooth where insertion of the implant along the distally adjacent tooth would cause its perforation

Sometimes, however, the initial conditions for starting treatment are so difficult that it is necessary to apply immediate implant loading. In particular, it is justified in the case where cross-sections of the bone base make it impossible to perform other treatments. Such complex cases require the collaboration of a team consisting of a dental surgeon, prosthodontist, dental engineer, and dental assistant.

An example of the use of immediate implantation immediately after tooth extraction and the installation of a long-term prosthetic restoration immediately after the completion of the surgical part of the treatment is the treatment plan prepared by the Author's team in June 2023, which will be presented as an example (Fig. 49). A 65-year-old patient presented with six incisors of the lower arch in a significant inclination concerning the bone base, along with almost complete exposure of the teeth in the vestibular zone, which made it impossible to perform an effective and useful prosthetic reconstruction with the use of the teeth. In the lateral zones, an insufficient bone base for implantation was found. The canal of the lateral alveolar nerve ran along the top of the alveolar process. The teeth were qualified for extraction. The problem was the unusual shape of the alveolar process expected after tooth extraction, making it impossible to place implants without additional procedures.

In the first place, it was necessary to perform a procedure consisting of the following stages:

1. tooth extraction;
2. separation of the periosteum;
3. correction of the alveolar process using a previously prepared template made of titanium using the additive 3D printing method - the template was bone and mucous;
4. installation of the second template for screwing in the implants;
5. installation of a ready-made prosthetic solution, i.e., an individual beam made in additive manufacturing by 3D printing from titanium directly following the assumed location of the implants;
6. installation of a previously prepared prosthetic work, in this case, a prosthesis reinforced with a titanium core.

The procedure was successful. After four months, the retention elements increasing the forces transmitted by the implants were replaced.

The aesthetic effect achieved was very high. It was also possible to correctly reconstruct the relation between the upper and lower arches. At the top, for financial reasons, the patient decided to use a skeletal prosthesis based on the rudimentary dentition of the molars as a temporary solution.

The procedure proved that it is possible to perform implantation based on an implant template not attached with additional pins to the bone base. It enables a radical change in the alveolar process with soft tissue reduction and immediate implantation and assembly of a ready, final prosthetic restoration. There is no need to use temporary restorations based on acrylate dentures.

12. Development of a general concept of a research, design, and production centre for prosthetic restorations and virtual acquisition of diagnostic data from cooperating dental clinics

To sum up this monograph, it should be emphasised that numerous original publications, patent solutions, completed projects, and awards at the International Innovation Fair organized with the support of the World Intellectual Property Organization WIPO, as well as clinical experience related to the treatment of thousands of dental patients in Author's clinic, confirmation of the placement of over 1000 implants with the use of implant guides according to the development of the concept confirms the originality of the approach and indicates the innovative nature of the achievements to date briefly presented in the monograph. It should be noted that, in essence, the process of designing and manufacturing prosthetic restorations does not differ from the very advanced production of elements of an aeroplane or a passenger car. In the case of prosthetic elements, the complexity of the shape of individual elements is much greater than in the case of elements with regular geometric shapes used in the industry, e.g., aviation. Prosthetic elements have millions of triangles that represent the organic shapes of the patient's tissues. Of course, the element itself does not have as many parts as, for example, aircraft engines,

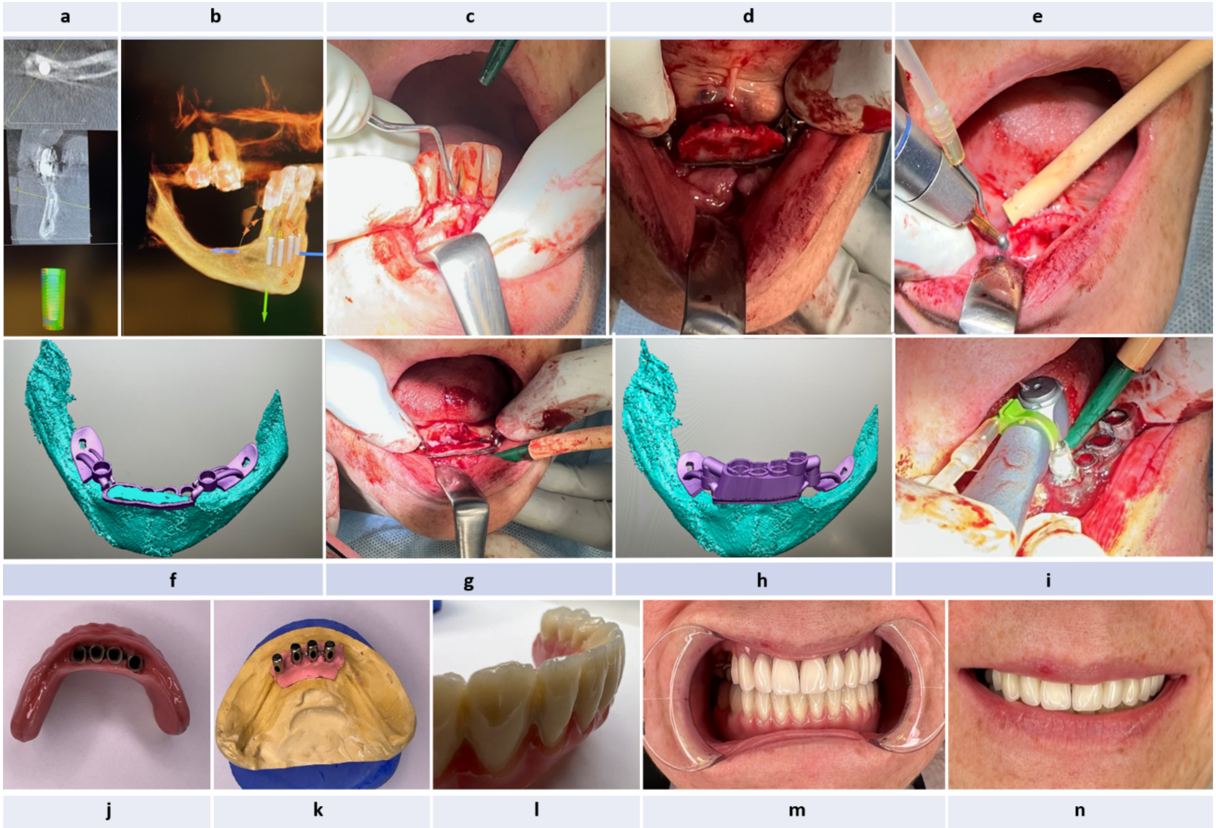


Fig. 49. The sequence of implementation of the treatment plan consisting of the extraction of the incisors of the lower arch along with the correction of the alveolar process to a position enabling immediate implantation along with the burden of the final prosthetic work a), b) the initial state on the tomogram illustrating the complexity of the clinical situation before the start of the procedure, c) the view of the patient's teeth during the extraction, d) control of the passing ability of the osseous template after periosteum detachment and before the start of the correction procedure, e) initiation of the alveolar correction procedure by the dental surgeon, f) design of the alveolar process after correction, g) intraoral intraoperative view, h) view of the design of the overlay on the osseous template enabling the insertion of implants, i) intraoperative view during bone drilling with the use of the implant template, j), k), l) view of the finished prosthetic work – view of the titanium hygienic bridge with primary telescopic crowns with integrated individual abutments, m), n) finished prosthetic work after installation in the oral cavity

but their irregular shape and very small size, where the walls of individual elements are often about 0.3 mm in cross-section. The accuracy of prosthetic elements must be counted in micrometres, posing great technological and design challenges as other engineering elements used in other industries. The functional functions of these products are simpler than those used in the aerospace or automotive industries. Many years of experience have led to the launch of a constantly developed production centre for prosthetic restorations with a virtual structure for obtaining diagnostic data from cooperating dental clinics, the diagram of which is presented (Fig. 50).

An important aspect of the current work system is the close cooperation between the dental clinic and the dental engineering centre at every stage of treating prosthetic and implant prosthetic patients. Implementing complex design and manufacturing procedures carefully and a full protocol for applying the technology in specific clinical cases is important. It requires training for both dentists and dental engineers. The number of cooperating clinics, currently relatively limited, is being systematically increased as part of the implemented business scaling plan, closely related to the plan to acquire further research and implementation projects in subsequently announced competitions. Supplementing the delivery system with the D2D door-to-door principle enables efficient implementation of dental engineering services related to the fully personalises and highly efficient design and manufacture of implants, especially prosthetic restorations, by the dental engineering centre, which closely cooperates with many dental clinics

Fig. 50. The target diagram of horizontal and vertical integration in smart centres for the manufacturing of dental prosthetic restorations, including an example of a technological line and an indication of the methods of virtual transfer of the results of tomographic diagnostic examinations of patients from dental clinics and physical transfer door-to-door of personalised fully manufactured prosthetic restorations with implantological templates and technical treatment plan to these clinics

specializing in implantology and dental prosthetics. This state-of-the-art idea on a global scale, which has been implemented for several years now in the realities of it's the Author's manufacturing centre and the Author's dental clinic, as well as within its projects, requires wide acceptance and understanding in medical circles and deserves full financial support under research and implementation funding systems.

The Author's work and his team confirm that the use of advanced technology for prosthetic and implant prosthetic treatment has a practical justification. Thanks to the implemented solutions, it is possible to perform effective, long-term tooth reconstruction in patients previously disqualified from implant procedures due to numerous complications in previous treatment or natural ageing processes causing the degradation of the bone base. At the same time, thanks to the developed protocol, which considers the planning of the entire treatment using modern CAD software, it is possible to significantly reduce the time necessary to carry out dental procedures from the initial visit. In particular, the implantation procedure can take up to 4 times shorter than without implant guides. Thanks to the fact that there is no need to detach the periosteum along the entire width of the alveolar process, the templates do not require attaching with additional pins, and single drills guarantee the correct placement of the implant in the bone base. In addition, prosthetic procedures can take place during 2-3 visits to the dentist's office, and even with the use of acrylic veneered solutions, it is possible to perform permanent prosthetic restoration installation during two visits. It allows the entire procedure to be shortened to 4 visits. It is also possible, under certain conditions, to perform prosthetic work before the implants are placed and to perform the procedure of immediate loading of the implants with the final prosthetic restoration during one procedure. Therefore, modern technology makes it possible to shorten the patient's convalescence period after the procedure to the minimum, reduce the number of necessary visits, and make it possible to perform full dental restoration in patients from abroad without compromising on the type of final prosthetic work performed. In addition, the patient spends about 3-5 hours in the dentist's chair during the entire treatment.

The results of the presented research also allow for a significant reduction in the time of the production process of prosthetic restorations. In particular, using 3D printing as the basic production process for all prosthetic and implant guide elements is a breakthrough. Currently, using CNC milling technology in prosthetic laboratories is a standard. It is known from experience that additive manufacturing by 3D printing methods of metal elements allows for reducing the production time by up to 20 times (!) if it is compared to the time of manufacturing procedures of high elements exceeding 25 mm on basic milling machines dedicated to dentistry by reducing the time by five times in the case of comparison to professional CNC milling centres. In addition, with a minimum extension of the process, it is possible to produce more than one element during this time. Another undeniable benefit is the reduction of the time necessary to carry out the post-production process of the elements. In the case of milled elements, it is necessary to correct the shape of the cut-off supports, and it is also necessary to compensate for arcades and under-milled zones, which are unavoidable. In the case of additively manufactured components using 3D printing, it is only necessary to smooth the support zones. The process can be done even in automatic devices. The optimal use of these possibilities allows for a qualitative leap in terms of both ensuring the technological parameters of the prosthetic restoration and the method of its installation, which brings only benefits to patients and dentists in everyday dental practice, significantly facilitating the production of comprehensive prosthetic restorations of the entire oral cavity.

13. The general conclusion

It is extremely important to conclude this monograph that all the achievements described here are based on comprehensive research results related to the study of the structure and properties of engineering materials, especially titanium and cobalt alloys used in dentistry, subjected to additive manufacturing using the Selective Laser Sintering (SLS) method and surface treatment using the Atomic Layer Deposition (ALD) method, as a domain of materials engineering in the context of the 3 x I 4.0/5.0 Integrated Industry Idea model, widely used methods of virtual design and computer-aided manufacturing, and the principle of Six Expectations Principle 6 x E as a materials engineering paradigm. The results of biological studies of materials produced in this way are significant in this approach, leading to numerous applications in the Author's clinical practice in cooperation with dentists. As a result of advanced virtual design processes, an appropriately selected engineering material subjected to appropriate technological processes obtains the appropriate shape and geometrical features, exhibiting an appropriate structure that ensures both appropriate mechanical, physicochemical, and biological properties, which guarantees appropriate functionality in this case of titanium and cobalt alloys used for prosthetic restorations in dentistry. Expectation can, therefore, be understood in this way as appropriateness.

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Contributions

The article was prepared independently by the Author (concept, writing, proofreading, supervision, selection of figures and tables, literature compilation, conclusions, management or co-management of source works, personal implementation of all technological and design works, participation in the implementation of research works and medical treatments, preparation of results tests and treatments and development of conclusions resulting from them) based on data contained in the author's projects and literature items cited in the article.

References

[1] L.A. Dobrzański, L.B. Dobrzański, Overview of the sustainable development of modern dentistry for the prevention of dental diseases, treatment with significant technological support, and the safety of patients and dentists, keynote lecture at the 4th World Congress on Dentistry and Maxillofacial Surgery, Paris, France, 6-8 February 2023.

[2] L.A. Dobrzański, L.B. Dobrzański, Unity of models for the development of advanced materials and their processing technologies, industry's integrated idea, and dentistry's sustainable development, invited lecture at the 23rd Physical Metallurgy and Materials Science Conference Advanced Materials and Technologies AMT'2023, Wisła, Poland, 18-21 June 2023.

[3] L.A. Dobrzański, L.B. Dobrzański, To what extent does modern dental engineering fit into the integrated model of the industry sustainable development, which takes into account the expectations of consumers, keynote lecture at the 5th World Congress on Dentistry and Maxillofacial Surgery, Rome, Italy, 18-20 September 2023.

[4] L.B. Dobrzański, The innovative technology of additive manufacturing of Dental prosthetic restorations using multi-component titanium alloys with aluminum and vanadium and cobalt alloys with chromium, keynote lecture at the 5th World Congress on Dentistry and Maxillofacial Surgery, Rome, Italy, 18-20 September 2023.

[5] L.B. Dobrzański, Innovative technology for additive manufacturing of prosthetic tooth restorations using multi-component titanium alloys with aluminum and vanadium and cobalt alloys with chromium, XXI Biomaterials and Mechanics in Dentistry Conference, Ustroń, 12-15 October 2023 (in Polish).

[6] L.A. Dobrzański, L.B. Dobrzański, J. Dobrzańska, Chapter 8. Ethical imperatives towards the development prospects of the triad of Dentistry 4.0, dental engineering, and nanoengineering, in: M.H. van

de Voorde, G. Jeswani (eds), Ethics in Nanotechnology: Social Sciences and Philosophical Aspects, de Gruyter, Berlin, Germany, 2021, 157-248. DOI: https://doi.org/10.1515/9783110719932-008
[7] L.A. Dobrzański, A.D. Dobrzańska- Danikiewicz, L.B. Dobrzański, Effect of Biomedical Materials in the Implementation of a Long and Healthy Life Policy, Processes 9/5 (2021) 865. DOI: https://doi.org/10.3390/pr9050865
[8] L.A. Dobrzański, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, J. Dobrzańska, The Concept of Sustainable Development of Modern Dentistry, Processes 8/12 (2020) 1605. DOI: https://doi.org/10.3390/pr8121605
[9] L.A. Dobrzański, L.B. Dobrzański, Approach to the design and manufacturing of prosthetic dental restorations according to the rules of the Industry 4.0, Materials Performance and Characterization 9/1 (2020) 394-476. DOI: https://doi.org/10.1520/MPC20200020
[10] L.A. Dobrzański, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Non-Antagonistic Contradictoriness of the Progress of Advanced Digitized Production with SARS-CoV-2 Virus Transmission in the Area of Dental Engineering, Processes 8/9 (2020) 1097. DOI: https://doi.org/10.3390/pr8091097
[11] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Gold Medal at the Kaohsiung International Invention and Design Expo, Kaohsiung, Taiwan, 10-12 December 2020.
[12] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Gold Medal at the International Invention and Design Competition "IIDC 2020", Hong Kong, China, 2-4 December 2020.
[13] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Gold Medal at the International Inventions and Innovations Competition "Sahasak Nimavum-2020", Colombo, Sri Lanka, 1-3 July 2020.
[14] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Best Presentation Award at the Malysia Technology Expo "MTE 2020", COVID-19 International Innovation Awards, Kuala Lumpur, Malysia, 20-22 February 2020.
[15] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, IFIA Best Invention Medal at the Malysia Technology Expo "MTE 2020", COVID-19 International Innovation Awards, Kuala Lumpur, Malysia, 20-22 February 2020.
[16] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Gold Medal at the Malysia Technology Expo "MTE 2020", COVID-19 International Innovation Awards, Kuala Lumpur, Malysia, 20-22 February 2020.
[17] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Gold Medal at the 4th World Invention Academic Conference "WIAC 2020", Seoul, Korea, 1.10-15.11.2020.
[18] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Special Award at the 4th World Invention Academic Conference "WIAC 2020", Seoul, Korea, 1.10-15.11.2020.
[19] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Gold Medal at the 14 th International Exhibition of Inventions "IWIS 2020", ONLINE, Warsaw, Poland, 19-21.10.2020.
[20] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, TOP 20 BEST INVENTION AWARDS at the 5th International Invention Innovation Competition in Canada "iCAN 2020", Toronto, Canada, 29.08.2020.
[21] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Gold Medal at the 5th International Invention Innovation Competition in Canada "iCAN 2020", Toronto, Canada, 29.08.2020.

[22] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Accessory for personal protection of dental staff against SARS-CoV-2 coronavirus and other pathogenic microorganisms, Special Award at the 5th International Invention Innovation Competition in Canada "iCAN 2020", Toronto, Canada, 29.08.2020.

[23] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, K. Rudziarczyk, A. Achtelik-Franczak, Patent application P.434391, Accessory for personal protection of dental staff against the SARS-CoV-2 coronavirus and other pathogenic microorganisms, filing date June 19, 2020 (in Polish).

[24] L.B. Dobrzański (project manager), Research and development work in the field of dental engineering for the client in the development of a globally innovative concept for securing a dental office during the COVID19 pandemic (in Polish).

[25] L.B. Dobrzański, Structure and properties of the engineering materials for prosthetic restorations of the stomatognathic system produced by additive and loss technologies, PhD Thesis, AGH University of Science and Technology, Kraków, 2018 (in Polish).

[26] L.B. Dobrzański, A. Achtelik-Franczak, J. Dobrzańska, L.A. Dobrzański, The digitisation for the immediate dental implantation of incisors with immediate individual prosthetic restoration, Journal of Achievements in Materials and Manufacturing Engineering 97/2 (2019) 57-68.
DOI: https://doi.org/10.5604/01.3001.0013.8541

[27] L.B. Dobrzański, A. Achtelik-Franczak, J. Dobrzańska, P. Pietrucha, Application of polymer impression masses for the obtaining of dental working models for the stereolithographic 3D printing, Archives of Materials Science and Engineering 95/1 (2019) 31-40.
DOI: https://doi.org/10.5604/01.3001.0013.1015

[28] L.B. Dobrzański, P. Malara, Chapter 9: Methodology of computer-aided design and production of dental prosthetic restorations from solid engineering materials, in: L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz (eds), Microporous and solid metallic materials for medical and dental applications, Open Access Library, Annal VII(1), International OCSCO World Press, Gliwice, 2017, 500-534 (in Polish).

[29] P. Malara, L.B. Dobrzański, Chapter 1: Strategies for computer-aided designing of surgical guides for dental implant procedures based on cone beam computed tomography, in: D. Carter (ed), Computed Tomography: Advances in Research and Applications, Nova Science Publishers, Hauppauge, NY, 2017, 1-22.

[30] P. Malara, L.B. Dobrzański, Screw-retained full arch restorations – methodology of computer aided design and manufacturing, Archives of Materials Science and Engineering 83/1 (2017) 23-29.
DOI: https://doi.org/10.5604/01.3001.0009.7538

[31] P. Malara, L.B. Dobrzański, Computer aided manufacturing and design of fixed bridges restoring the lost dentition, soft tissue and the bone, Archives of Materials Science and Engineering 81/2 (2016) 68-75.
DOI: https://doi.org/10.5604/01.3001.0009.7101

[32] P. Malara, L.B. Dobrzański, J. Dobrzańska, Computer-aided designing and manufacturing of partial removable dentures, Journal of Achievements in Materials and Manufacturing Engineering 73/2 (2015) 157-164.

[33] P. Malara, L.B. Dobrzański, Designing and manufacturing of implantoprosthetic fixed suprastructures in edentulous patients on the basis of digital impressions, Archives of Materials Science and Engineering 76/2 (2015) 163-171.

[34] P. Malara, L.B. Dobrzański, Computer-aided design and manufacturing of dental surgical guides based on cone beam computed tomography, Archives of Materials Science and Engineering 76/2 (2015) 140-149.

[35] L.B. Dobrzański (project manager), CODIDENT Research, Development and Implementation Project, Increasing competitiveness and diversification of dental services through the implementation of an innovative system for performing prosthetic works and an innovative dental diagnostic system, Gliwice, 2013-2015 (in Polish).

[36] L.B. Dobrzański (project manager), CODIDENT Research, Development and Implementation Project, Development of technology for the production of innovative prosthetic restorations using CAD/CAM technology, Gliwice, 2013-2015 (in Polish).

[37] L.B. Dobrzański (project manager), Development and implementation works related to the implementation of innovative prosthetic restorations manufactured using SLS/SLM 3D printing technology (in Polish).

[38] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, L.B. Dobrzański, J. Dobrzańska (eds), Synthesis and Characterization of Biomedical Materials, MDPI, Basel, 2021. DOI: https://doi.org/10.3390/books978-3-0365-2523-5

[39] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, L.B. Dobrzański, J. Dobrzańska, The Importance of Synthesis and Characterization of Biomedical Materials for the Current State of Medicine and Dentistry, Processes 9/6 (2021) 978. DOI: https://doi.org/10.3390/pr9060978

[40] L.B. Dobrzański, Anna Achtelik-Franczak, J. Dobrzańska, L.A. Dobrzański, Comparison of the Structure and Properties of the Solid Co-Cr-W-Mo-Si Alloys Used for Dental Restorations CNC Machined or

Selective Laser-Sintered, Materials Performance and Characterization 9/4 (2020) 556-578.
DOI: https://doi.org/10.1520/MPC20200023

[41] L.A. Dobrzański, L.B. Dobrzański, A. Achtelik-Franczak, J. Dobrzańska, Application Solid Laser-Sintered or Machined Ti6Al4V Alloy in Manufacturing of Dental Implants and Dental Prosthetic Restorations According to Dentistry 4.0 Concept, Processes 8/6 (2020) 664. DOI: https://doi.org/10.3390/pr8060664

[42] L.A. Dobrzański, L.B. Dobrzański, Dentistry 4.0 Concept in the Design and Manufacturing of Prosthetic Dental Restorations, Processes 8/5 (2020) 525. DOI: https://doi.org/10.3390/pr8050525

[43] L.A. Dobrzański, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, Additive and hybrid technologies for products manufacturing using powders of metals, their alloys and ceramics, Archives of Materials Science and Engineering 102/2 (2020) 59-85.
DOI: https://doi.org/10.5604/01.3001.0014.1525

[44] L.A. Dobrzański, A.D. Dobrzańska- Danikiewicz, Z.P. Czuba, L.B. Dobrzański, A. Achtelik-Franczak, P. Malara, M. Szindler, L. Kroll, The new generation of the biological-engineering materials for applications in medical and dental implant-scaffolds, Archives of Materials Science and Engineering 91/2 (2018) 56-85.
DOI: https://doi.org/10.5604/01.3001.0012.5490

[45] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, Z.P. Czuba, L.B. Dobrzański, A. Achtelik-Franczak, P. Malara, M. Szindler, L. Kroll, Metallic skeletons as reinforcement of new composite materials applied in orthopaedics and dentistry, Archives of Materials Science and Engineering 92/2 (2018) 53-85. DOI: https://doi.org/10.5604/01.3001.0012.6585

[46] L.B. Dobrzański, Chapter 4: Mechanical Properties Comparison of Engineering Materials Produced by Additive and Subtractive Technologies for Dental Prosthetic Restoration Application, in: L.A. Dobrzański (ed), Biomaterials in Regenerative Medicine, IntechOpen, Rijeka, 2018, 111-140. DOI: http://dx.doi.org/10.5772/intechopen.70493

[47] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, A. Achtelik-Franczak, L.B. Dobrzański, T.G. Gaweł, Patent No. PL229148, Implanto-scaffold or prosthesis of anatomical elements of the stomatognathic system and facial skeleton, date of granting the right: January 9, 2018 (in Polish).

[48] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, L.B. Dobrzański, A. Achtelik-Franczak, Patent No. PL237449, Biological-engineering composites for regenerative medicine, date of granting the right: January 24, 2020 (in Polish).

[49] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, A. Achtelik-Franczak, Patent No. PL241034, Highly developed bone implant, including the facial skeleton, date of granting the right: May 10, 2022 (in Polish).

[50] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, A. Achtelik-Franczak, Patent application P.434312, Highly surface-developed dental implant, filing date June 15, 2020 (in Polish).

[51] L.A. Dobrzański, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, Manufacturing technologies thick-layer coatings on various substrates and manufacturing gradient materials using powders of metals, their alloys and ceramics, Journal of Achievements in Materials and Manufacturing Engineering 99/1 (2020) 14-41. DOI: https://doi.org/10.5604/01.3001.0014.1598

[52] L.B. Dobrzański (Deputy Project Manager, Deputy R&D Manager, Production Manager, Head of the CAD/CAM Studio), IMSKA-MAT Innovative dental and maxillofacial implant scaffolds manufactured using innovative additive technology supported by computer material design ADD-MAT, Gliwice, 2017-2023 (in Polish).

[53] J. Dobrzańska, L.B. Dobrzański, L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, K. Gołombek, What Are the Chances of Resilon to Dominate the Market Filling Materials for Endodontics?, Metals 11/11 (2021) 1744.
DOI: https://doi.org/10.3390/met11111744

[54] L.A. Dobrzański, J. Dobrzańska, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, K. Gołombek, Development Strategy of Endodontic Filling Materials Based on Engineering and Medical Approaches, Processes 9/11 (2021) 2014.
DOI: https://doi.org/10.3390/pr9112014

[55] J. Dobrzańska, L.B. Dobrzański, L.A. Dobrzański, K. Gołombek, A.D. Dobrzańska-Danikiewicz, Is Gutta-Percha Still the "Gold Standard" among Filling Materials in Endodontic Treatment?, Processes 9/8 (2021) 1467. DOI: https://doi.org/10.3390/pr9081467

[56] J. Dobrzańska, L.B. Dobrzański, K. Gołombek, L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, Virtual Approach to the Comparative Analysis of Biomaterials Used in Endodontic Treatment, Processes 9/6 (2021) 926. DOI: https://doi.org/10.3390/pr9060926

[57] L.A. Dobrzański, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, M. Kraszewska, Manufacturing powders of metals, their alloys and ceramics and the importance of conventional and additive technologies for products manufacturing in Industry 4.0 stage, Archives of Materials Science and Engineering 102/1 (2020) 13-41.
DOI: https://doi.org/10.5604/01.3001.0014.1452

[58] L.A. Dobrzański, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, Overview of conventional technologies using the powders of metals, their alloys and ceramics in Industry 4.0 stage, Journal of Achievements in

Materials and Manufacturing Engineering 98/2 (2020) 56-85.
DOI: https://doi.org/10.5604/01.3001.0014.1481

[59] L.A. Dobrzański, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, J. Dobrzańska, M. Kraszewska, Chapter 7: The synergistic ethics interaction with nanoengineering, dentistry, and dental engineering, in: M.H. van de Voorde, G. Jeswani (eds), Ethics in Nanotechnology: Emerging Technologies Aspects, de Gruyter, Berlin, 2021, 119-190.
DOI: https://doi.org/10.1515/9783110701883-007

[60] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, A. Achtelik-Franczak, L.B. Dobrzański, T.G. Gaweł, Patent No. PL229149, Implanto-bone scaffold, date of granting the right: January 9, 2018 (in Polish).

[61] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, L.B. Dobrzański, A. Achtelik-Franczak, M. Kremzer, Patent No. PL236090, Method of producing composite materials with a microporous skeleton reinforcement structure, date of granting the right: December 16, 2019 (in Polish).

[62] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, L.B. Dobrzański, A. Achtelik-Franczak, T.G. Gaweł, Implant-scaffold or Prosthesis Anatomical Structures of the Stomatognathic System and the Craniofacial, Gold Medal at the International Exhibition of Technical Innovations, Patents and Inventions "INVENT ARENA 2016", Třinec, Czech Republic, 16-18.06.2016.

[63] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, L.B. Dobrzański, A. Achtelik-Franczak, T.G. Gaweł, Implant-scaffold or Prosthesis Anatomical Structures of the Stomatognathic System and the Craniofacial, Gold Medal at the International Intellectual Property, Invention, Innovation and Technology Exposition "IPITEX 2016", Bangkok, Thailand, 2-6.02.2016.

[64] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, L.B. Dobrzański, A. Achtelik-Franczak, T.G. Gaweł, Implant-scaffold or Prosthesis Anatomical Structures of the Stomatognathic System and the Craniofacial, International Intellectual Property Network Forum (IIPNF) Leading Innovation Award at the International Intellectual Property, Invention, Innovation and Technology Exposition "IPITEX 2016", Bangkok, Thailand, 2-6.02.2016.

[65] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, T.G. Gaweł, L.B. Dobrzański, A. Achtelik-Franczak, The novel composite consisting of a metallic scaffold, manufactured using a computer aided laser method, coated with thin polymeric surface layer for medical applications, Semi Grand Prize at the Global Inventions and Innovations Exhibitions Innova Cities Latino-America "ICLA 2015", Foz do Iguaçu, Brazil, 10-12.12.2015.

[66] L.A. Dobrzański, A.D. Dobrzańska-Danikiewicz, P. Malara, T.G. Gaweł, L.B. Dobrzański, A. Achtelik-Franczak, The novel composite consisting of a metallic scaffold, manufactured using a computer aided laser method, coated with thin polymeric surface layer for medical applications, Gold Medal at the 9th International Warsaw Invention Show "IWIS 2015", Warsaw, Poland, 12-14.10.2015.

[67] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, A. Achtelik-Franczak, K. Rudziarczyk, Patent application P.434313, Dental implant mounting accessory, filing date June 15, 2020 (in Polish).

[68] L.B. Dobrzański, L.A. Dobrzański, J. Dobrzańska, A. Achtelik-Franczak, Patent application P.434315, System for attaching a crown to a dental implant, filing date: June 15, 2020 (in Polish).