2019 ADDITIVE MANUFACTURING MEETING

DISCOVER

3D Printing

International AM Users' Conference

PROCEEDINGS BOOK

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Wrocław, Poland

18–19 SEPT, 2019

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Oficyna Wydawnicza Politechniki Wrocławskiej • Wrocław 2019

Conference Organizers
Centre of Advanced Manufacturing Technologies (CAMT-FPC)
Mechanical Faculty of Wroclaw University of Science and Technology

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Welcome

Additive Manufacturing Meeting (AMM) is an annual event, organized by Centre of Advanced Manufacturing Technologies (CAMT-FPC) and Faculty of Mechanical Engineering of Wroclaw University of Science and Technology. Since this year AMM became a conference.

The AMM conference is focused on building a platform for an exchange of knowledge and experience between research and industrial institutions in the field of Additive Manufacturing ("3D printing"). The conference program addresses issues like CAx modeling, manufacturing, new materials, process development and AM applications.

The plenary talks within the Conference are held by highly qualified experts and researchers of AM industry from Poland, Austria, Czech Republic, Finland, Germany, Ireland and Singapore. For the first time, students, Ph.D. candidates and young scientists (up to 35 years old) have the opportunity to present their achievements in the development of AM during the Young Scientists Poster Session on the second day of the conference. Different formats are used at the Conference AMM2019 including plenary talks, workshops, poster session, technical exhibition as well as lab visit to CAMT-FPC. Apart from the main program, AMM networking session is an excellent occasion to establish business contacts between representatives of universities, research centers and industry. Such variety of activities contributes in creating a common platform for exchange of knowledge and experience both in the field of industrial solutions and research development in the field of AM.

The AMM program is designed to challenge and inspire you in the field of additive manufacturing industrial implementation. The thematic panels of this year' conference are Analysis and Simulation, Biomedical Applications, Novel Applications, Business Solutions in AM and Industrial Cases of AM Implementation.

The AMM Conference takes place in Wroclaw, one of the most beautiful cities in Poland. Wroclaw is a very picturesque city with a large number of green areas, parks and 115 bridges across 5 rivers crossing the city. Wroclaw is an excellent example of a multicultural metropolis located at the crossroads of ethnically diverse regions.

We are delighted to meet all our speakers, partners and participants at the 3rd International Conference "AMM: 3D Printing in Industrial and Medical Applications"!

Organizing Team of AMM2019

About CAMT-FPC

The research unit CAMT-FPC (Centre of Advanced Manufacturing Technologies – Fraunhofer Project Center CAMT-FPC) was established in 2008 at the Faculty of Mechanical Engineering of the Wrocław University of Science and Technology. As part of the international Fraunhofer Project Center (FPC) created together with Fraunhofer Geselschaft from Dresden in the field of laser and additive manufacturing (AM) technologies. Together with foreign scientific partners, as well as Polish and foreign companies from the automotive, aviation, medical and pharmaceutical industries, CAMT-FPC is leading Polish industrial research in the field of design, development and application of lasers, additive manufacturing and hybrid technologies.

Main competences of CAMT-FPC include the use of AM technologies to manufacture individualized components and fully functional parts with a complex internal and external structure, including elements designed to work in difficult (thermal, mechanical and corrosive) working conditions.

CAMT-FPC carries out research and development projects in the field of material and mechanical control for a wide spectrum of engineering materials (ceramics, polymers, metals and super alloys) intended for applications in various industries (automotive, aviation, medicine, energy) produced by additive technologies (SLM, EBM, SLS, FDM, etc.).

Research offer of CAMT-FPC includes:

- Additive Manufacturing (AM) Technologies
- Surface Functionalization
- CAD / CAM / CNC Planning
- Personalized Solutions in the Field of Biomedical Engineering
- Reverse Engineering (RE)
- Computed Tomography (CT)
- Material Properties Characterization
- Research in the Field of Mechatronics and Vision Systems
- Automation and Robotization of Manufacturing Processes
- Integration of IT Systems in Production
- Organization and Optimization of Production Processes
- Consultancy in the Area of Product Development.

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OPENING OF AMM2019

Case Studies of SLM Technology in Key Markets

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Keywords: SLM®, industrial components, productivity, technology development, digital production

Abstract

Selective Laser Melting is being increasingly adopted as the manufacturing method of choice for different types of industrial parts. They include space and aerospace components, automotive components, medical components, power components and tooling components. The presentation will address several key technical developments that contribute to the productivity of the Selective Laser Melting process. The impact of multi-laser SLM systems, advanced gas flow management, quality control systems and advanced data preparation software on the productivity of the SLM® process will be addressed during this session.

The Influence of Gas Flow During the Selective Laser Melting of Ti6Al4V

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Keywords: SLM, Titanium alloy, gas flow, process characterisation

Abstract

Selective laser melting is an additive manufacturing technology which is frequently employed in the manufacturing of complex metallic components. One such metal, Ti6Al4V is a titanium alloy which is commonly used in the biomedical, aerospace and automotive industries. Selective laser melting of this material involves melting the powder material through laser irradiation in a successive layer by layer manner. Though more than 150 process parameters have been identified, one crucial input which influences the process stability and thus the part quality is the inert gas which flows within the process chamber [1].

The main purpose of the gas flow is to enable the required inert atmosphere however, a secondary function is to remove process by-products which may interfere with the laser. This study investigates the effect of the gas flow during selective laser melting of Ti6Al4V in the chamber of a Realizer SLM50. Using CFD a predicted gas flow within the chamber was established for multiple flow rates as well as for a new gas inlet baffle which was designed to improve the flow across the build plate.

Empirical investigations using the initial chamber conditions as well as the new baffle design were conducted. For each design a number of gas flow rates were considered. Both single line scans as well as cylindrical and cuboid shaped samples were manufactured and examined using a variety of microscopy, computed tomography and density characterisation techniques. Results are presented regarding the; uniformity of the gas flow and spatter distribution across the build plate as well as laser beam attenuation as a function of gas flow.

SESSION 2

ANALYSIS AND SIMULATION IN AM

Recent Enhancements in Additive Manufacturing Simulation

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Keywords: Simufact Additive, simulation

Abstract

3D printing of metal components gives opportunity to shift manufacturing technology to the next level. The lack of manufacturing constraints known from conventional manufacturing allows to create parts with pure functional design, which may be tailored to meet individual requirements. On the other hand, this approach is currently limited to small lot sizes, thus requiring a first-time-right approach for economic reasons. The prediction of the parts' shape and properties becomes an indispensable requirement in the process design phase. This can be achieved through implementation of an accurate simulation of the part build stage and the necessary post processing steps.

The simulation of additive manufacturing processes on the part level requires a dedicated solution to balance the level of captured physics with required computational resources in terms of necessary hardware and computing time. With Simufact Additive, a build process simulation of a typical AM part runs in a couple of hours on conventional PC workstations. The output results include the deviations from CAD geometry, distortions, residual stresses and much more useful information to optimize the print process prior to the first printing.

Simufact Additive can be run on different accuracy levels: the fastest approach based on previously calibrated eigenstrains is proven to provide accurate results for materials with mild nonlinearity in thermal expansion. If, due to multiple phase transformation, significant volume change is observed in the temperature regime of the build process, this method will probably fail. To address such phenomenon which can be observed for instance in maraging steels, a pseudo-transient thermo-mechanical-metallurgical coupled analysis scheme has been introduced to Simufact Additives latest release. In this presentation, the methodology will be explained and illustrated on a practical example.

Numerical Simulation of Additive Manufacturing Process as Support for Real Industrial Cases

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Keywords: numerical simulation, Additive Manufacturing

Abstract

Additive Manufacturing (AM) has developed rapidly in the last few years and has demonstrated significant potential in establishing a highly customizable production process. While having great advantages, the material properties and product quality often remain uncertain. With virtual experimental campaigns explore the material properties to make innovative design decisions and part optimizations.

- Simulate to better observe the phenomenology and understand the effect of parameters onto material physics
- Anticipate the Product Performance to ensure the best material quality and performance early in the R&D phase
- Speed up innovation cycles, reduce try-outs and efficiently prevent print failures during production

With AM you can gain insight into the material properties to achieve innovative, cost-effective and error-free design, ultimately producing high quality and timely products.

Additive Manufacturing widely known as 3D printing, is a manufacturing process where a component is produced, layer by layer, from digital 3D data. AM has developed rapidly in the last 10 years and has demonstrated significant potential in cost reduction of performance-critical components. This can be seen through improved design freedom, reduced material waste, and reduced post-processing steps.

Modelling AM processes not only provides important insight into competing physical phenomena that lead to final material properties and product quality, but also provides the foundation for qualification of the manufacturing process, exploiting the design space towards functional products and materials.

The length and timescales required to model AM processes and to predict the final workpiece characteristics are very challenging.

Models must deal with multiple physical aspects, such as heat transfer and phase changes, as well as the evolution of material properties and residual stresses throughout the build time. Therefore, the modelling task is a multi-scale, multi-physics endeavor calling for a complex interaction of multiple algorithms.

The article and presentation will demonstrate possibility of numerical simulation of AM with prediction of final component distortion and material quality prediction as porosity and material properties. The whole solution will be demonstrating on basic example and for industrial cases mainly from airplane industry.

Simulation of Single Track Laser Metal Deposition Process of Inconel 718 Using COMSOL Multiphysics

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Keywords: LMD, Laser Cladding, process simulation, mesh deformation

Abstract

Laser metal deposition (LMD) technology has become common in some industry branches, especially connected with processing hardly workable alloys, e.g. Inconel 718. It gives ability of deposition small amounts of such materials on complex surfaces. It is also increasingly used as an additive technology allowing building spatial objects [1].

Development of process parameters focuses on two main purposes: providing defect-free clad structure and obtaining desired geometry. Although the first requirement is often easy to achieve in case of similar substrate and additional material, the second strongly depends on the selected parameter set [2]. Commonly, in order to obtain proper combination of process parameters many experimental tests should be carried out.

Shortening of preliminary parameter set development by simulation study was proposed. Furthermore, this approach can give more information about phenomena occurring during the LMD process. Simulation also allows defining the influence of parameters, especially laser power, amount of added powder, travel speed [3] and shielding gas [4].

This study aims on prediction of the clad geometry based on simulation of heat transfer and fluid dynamics of the melted pool, particularly surface tension and viscosity of the liquid metal. Moreover, mesh deformation was involved to compute spatial displacement of the surface. Simulation model involves basic LMD process parameters: laser beam source with its travel velocity and amount of added powder. The output of the model consists of material and geometry data allowing further computation of next layer deposition.

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Coupled Thermo-Mechanical Simulation of a Laser Powder Bed Fusion Process

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Keywords: Additive Manufacturing, simulation, abaqus

Abstract

The additive manufacturing processes pose new challenges for simulation tools and methods. The localized heat sources and high temperature gradients cause the significant residual stresses which lead to distortions or even parts fracture and failure. The optimization of process window for additive manufacturing to avoid those problems is a challenge. The numerical simulations are commonly and successfully used to support many production processes, e.g. metal forming (welding, stamping, forging), plastic injection or even machining from many years. The computer aided engineering tools can be used to address additive manufacturing processes challenges [1]. They can help to overcome difficulties in production and enable to optimize the process and manufacturing parts but only if they are physical-based and accurate enough.

The presented simulation is the physical-based coupled thermo-mechanical analysis of the laser powder bed fusion process. The three-dimensional bridge-like structure was created based on the AMB2018–01 Additive Manufacturing benchmark published by the National Institute of Standards and Technology (NIST) [3]. The thermo-mechanical coupling is done in sequential manner. In the first step a transient heat transfer analysis is carried out. The material deposition and the laser beam path are taken into account. Next the field of the temperature is used as a load in the structural quasi-static analysis. The created model is based on example from Abaqus Example Problems Guide [2].

This analysis shows the unique Abaqus features intended for simulation of additive manufacturing processes like temperature-dependent thermal and mechanical properties of materials, coupled thermo-mechanical simulation, progressive element activation, heating by a moving nonuniform heat flux and cooling on evolving external surfaces. The obtained results like residual elastic strains and distortions caused by them correlate well with the physical process [4].

The presentation will focus on Abaqus modeling approaches and simulation techniques for coupled thermo-mechanical simulation of additive manufacturing process.

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Acceleration of Additive Manufacturing Process Through an Integrated End-to-End Software Solution in NX CAD/CAM/CAE

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Keywords: NX, CAM, Hybrid Additive Manufacturing, Additive Manufacturing, convergent modeling, topology optimization

Abstract

NX™ software provides a single, integrated system that meets the unique challenges of designing, optimizing and building metal and plastic components using the latest additive manufacturing methods. Because NX is a comprehensive platform for engineering design, simulation and manufacturing, you are able to combine special modeling functions with structural and topology optimization capabilities to develop groundbreaking designs using additive processes. By using NX you have the power to drive the latest additive manufacturing equipment, including powder bed 3D printers.

With Convergent Modeling technology, users can immediately begin using scanned data to design products. Combining convergent modeling with the capability to manufacture parts using 3D printing directly from NX simplifies the additive manufacturing process. The new scan edit-and-print workflow supports the 3D manufacturing format (3MF) and Microsoft's 3D print capabilities.

NX helps engineers set up the build tray and nest parts, and define necessary support structures to prepare the setup for 3D printing. The new NX solutions let you quickly load build tray configurations and easily position the printed parts using advanced capabilities. The build processor framework in NX provides support for a wide range of printers to generate the output to drive powder bed fusion 3D printers for plastic and metal parts.

The Simcenter™ 3D Additive Manufacturing solution can help manufacturers achieve a quality print the first time, saving enormous amounts of resources, cost and time. This solution uses a digital twin of the build tray, including parts, support structures and residual powder, to simulate the metal deposition process. This allows industrial manufacturers to adjust the printing process, improving the quality of the final print.

NX™ software provides support for new hybrid-manufacturing technologies in which additive manufacturing (3D printing or metal deposition) is incorporated with subtractive (cutting) methods in a traditional machine-tool environment. These manufacturing techniques will revolutionize the way we think about making parts. By building complex geometries, including internal cavities, and then machining them for tight tolerances as they are built, new classes of parts can be manufactured, or many setups may be consolidated into one.

SESSION 3

BIOMEDICAL APPLICATIONS

High-Resolution 3D Printing via Melt Electrowriting

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Keywords: melt electrowriting, 3D printing

Abstract

This lecture will show how an emerging 3D printing technology, melt electrostatic writing (melt electrowriting), will lead to new innovations in biomedical materials. This microscale 3D direct-writing technology can alter its diameter on-demand, and from the regulatory perspective builds on decades of using melt processing to manufacture medical devices. Melt electrowriting relies on the electrohydrodynamic effect of stabilizing fluid columns with an applied voltage, and results in a range of new 3D objects with microscale and nanoscale features. The benefit for the biomaterials community in particular is a robust, reproducible and low-cost manufacturing technology that can be researched in university settings while providing a path to the clinic.

Assessment of Cellular Reactivity to DNA Damage Caused by Contact with Materials Made with 3D Printing Technology, Dedicated to Face and Cranial Implants

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Keywords: Selective Laser Sintering, magnetron sputtering, genotoxicity, gene expression

Abstract

Jawbone resection is the final surgical treatment for ~5000 patients in EU28 with maxillofacial benign and malignant tumours. The resulting large bone defects lead to scarred, mangled facial appearance and the loss of mastication and speaking function, requiring facial aesthetic and functional reconstruction as basis for physical and physiologic rehabilitation.

As part of the work consisting in the assessment of genotoxicity of materials made in 3D printing technology, the following markings were carried out: chromosome damage research – micronucleus test; evaluation of the expression of selected genes related to the genotoxicity / DNA damage pathway effects. The assays were performed in an in vitro model on two cell lines using human osteoblasts and osteoblast-like tumor cells – SaOS-2. The tests were carried out in such a way that the roots were in contact with the test substrate for at least 72 hours. Joko positive control, which was supposed to cause a genotoxicity effect, was used in camptothecin. After the culture was completed on the test substrates, the cells were stained with fluorescent dyes – a micronucleus test (DNA Hoechstasis) and lysis for RNA isolation – in the case of the expression of selected genes. The assessment of the potential genotoxicity of the tested substrates was based on the analysis of the expression of selected genes associated with the genotoxicity / DNA damage pathway. The panel used included the following genes: ATR, MDM2, TP53, PPIA, ATM, CHEK1, CHEK2, and CDKN1A. The expression of selected genes was assessed using the Real-time PCR method using TaqMan molecular probes.

Acknowledgment: This project is implemented under the Program for M-ERA.NET-2016/232/2017 *Patient-specific bioactive, antimicrobial PLA-PGA/titanium implants for large jawbone defects after tumour resection* “jawIMPLANT”, funded by the National Centre for Research and Development.

SESSION 4

NOVEL APPLICATIONS

Roughness Influence on Self-Adaptation and Self-Healing of DLC-MoS_2 Wear Protective, Low-Friction Coatings on 3D Printed Polymers

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Keywords: Selective Laser Sintering, magnetron sputtering, polyamide, molybdenum disulfide, diamond-like carbon

Abstract

The 3D printing of polymers is becoming increasingly important as an industrial manufacturing process for small and medium series in automotive and aerospace production. However, the post-processing to fulfil the necessary mechanical-tribological properties for high-performance applications, e.g. for sliding bearings, are currently unsolved for common 3D printing thermoplast polymer materials. In particular, the high roughness of e.g. selective laser sintered (SLS) components from polyamide (PA12) poses a major challenge for any surface treatment.

This work solves this bottleneck by means of physical vapor deposition (PVD), applying coatings of solid lubricants (diamond-like carbon (DLC, a-C: H) and MoS_2) by high-power pulsed magnetron sputtering (HIPIMS) with a thickness of 4–5 µm, whereby the coating temperature is kept low (<60°C) to prevent polymer degradation or distortion. However, this thickness, chosen due to economic feasibility for future transfer to production, is significantly less than the substrate roughness of the PA12 surfaces after SLS layer-by-layer manufacturing and standard ball-blasting post-processing. Consequently, additional standard post-processing based on dip and spray coating with paints of different viscosity was performed in order to check the influence of reduced surface roughness on dry, unlubricated sliding under conditions of high Hertzian pressures.

Results show, that even extreme overloading conditions (Hertzian contact pressures of ~130 MPa) lead to only minimal wear at very low coefficients of friction (<0.15) in the performed reciprocal linear-tribological tests. For the non-organical coated PA12, especially a-C:H coatings with low MoS_2 content, a transfer of sheared coatings and polymer particles from roughness peaks in valleys (self-adaptation to the counterpart surface) occurs, whereby the formed transfer layer is rather free of cracks. After this run-in phase and the adaptation to the Al_2O_3 counterbody geometry, the friction mechanisms and level of friction coefficients are rather similar for coatings on dip/spray coated thermoset layers and on plain PA12.

Photopolymer Formulation for Microstereolithography 3D Printing and Ultra-Fast High-Efficiency High-Resolution Fabrication of Microlenses

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Keywords: Three-Dimensional (3D) Printing, Digital Light Processing (DLP), photopolymer formulation, microlens array, oscillation, optical surface roughness

Abstract

Photopolymer formulation to minimize feature size, surface roughness, and stair-stepping of microarchitectures fabricated using digital light processing-based 3D printing.

Achievement of maximum resolution is a key precursor to obtaining three-dimensional (3D) structural details suited for microstereolithographic applications. Here, we present a family of 'open-source' stereolithography printing materials optimized for maximum resolution and surface quality and minimal layering artifacts [1]. To illustrate the potential of our recently-developed multimaterial digital light processing (DLP)-based 3D printing system [2] to produce high-resolution, high-quality microarchitectures, we exploit a wide variety of resin formulations to determine optimal composition to yield maximum printing resolution and surface quality for a tailorable range of thermomechanical properties suited to novel applications in 3D printing of smooth free-form solids, micro-optics, and direct fabrication of microfluidic platforms with functional surfaces. The observed changes are explained in fundamental terms of the relationship between the optical photofield and reaction kinetics.

Oscillation-enabled greyscale lithography for rapid fabrication of ultra-smooth, controlled-shape micro-lens arrays.

Realization of optical clarity and surface smoothness is an antecedent to attaining micro-optical components of industrial grade. However, layering artifacts, intrinsic to all layer-by-layer 3D printing processes are a barrier to the betterment in the fidelity of such fabrication. Digital light processing-based systems such as projection microstereolithography (PμSL), which employs a digital micromirror device (DMD) as a dynamic photomask to precisely form solid structures, is found lacking by itself to achieve optically smooth surfaces, by virtue of non-uniformity in light intensity across the field of view. Its inherent projection discretization occasioned by the dead spaces in the discrete micromirrors matrix becomes a great obstacle in the fabrication of micro-optical devices with strict requirements in surface smoothness. The aim of this study is to integrate optical oscillation into the light engine modulator of PμSL to inherently eliminate surface roughness caused by discretization of images into a pixel array. Our new custom low-cost oscillation-integrated system, introduced alongside a family of custom-formulated photopolymers devised specifically for optical surfaces from our recent study [1], affords ultra-fast (within seconds), high-resolution, one-step direct fabrication of adaptable microlens array geometries consisting of symmetrical and asymmetrical microlenses with sub-micron accuracy and deep sub-wavelength surface roughness (<6 nm) without any required post-treatment by means of an optimized oscillation frequency innately eliminating the surface roughness. The developed technique, besides the field of microlens arrays, could provide instructive inspirations for numerous fields involving a plethora of mass production applications with high demands for ultra-smooth surfaces.

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4D Printing of Metallic Glass Composites

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Keywords: SLM, metallic glass, composite, 4D printing

Abstract

Due to a high specific strength, low stiffness and unique chemical properties, metallic glasses (MGs) are promising materials for numerous demanding applications. Despite extensive research in the last 50 years, still the wide application is rather a dream than a technical reality. The reasons are poor plasticity of MGs and severe limitations in the manufacturing process. While the first obstacle had been overcome by the creation of various Metallic Glass Matrix Composites (MGMCs) [1] only recently, thanks to Additive Manufacturing (AM) [2] revolution, MGs became available in any form regardless of Glass Forming Ability (GFA) [3].

This work presents a new approach to AM of MGMCs by introducing precise spatial distribution of amorphous and crystalline phases. As the phase composition is controlled together with shape of the object, we call it 4D printing with materials crystallinity as an additional controlled parameter.

The material used in this work is Zr-Cu-Al-Nb MG alloy with low GFA (AMZ4, Heraeus GmBH) and it has been processed via selective laser melting. Devitrification of such alloy is heating rate-sensitive, thus can be controlled in the Heat Affected Zone (HAZ) by variable laser parameters. Such ordered structures presented below promise exceptional properties compared to traditional MGs and MGMCs.

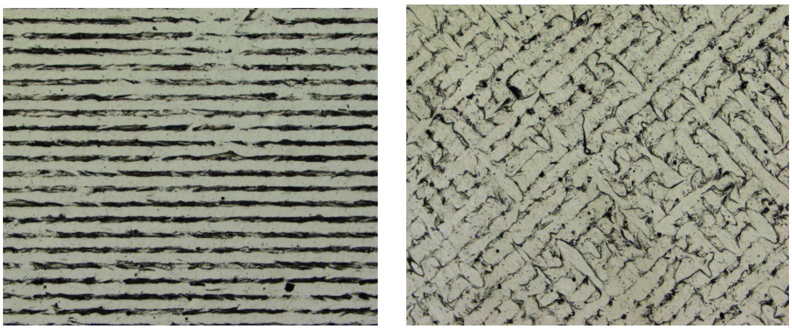

Fig. 1. Examples of crystalline (dark) – amorphous (white) composites obtained in the process

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SESSION 5

BUSINESS SOLUTIONS IN AM

Reducing Costs for AM Components with Nesting

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Keywords: SLM, AZ31, magnesium alloy, material characterization

Abstract

Additive Manufacturing is fantastic. It allows you to create shapes and forms unseen for engineers. It will give designers the freedom to create something that is truly needed instead of what is possible due to limitation of manufacturing technologies. Many different branches of industry are exploiting the advantages of additive manufacturing: aerospace, automotive, medical, arts and even construction.

Due to development in technology and spreading of knowledge of different applications, additive manufacturing is adapted more and more within the more traditional industry as well. In more traditional applications the benefits of AM are often an excellent bonus: reducing weight of components or consolidating them into more compact structures with fewer parts to mention a couple. However these benefits of AM are not as critical in decision making as in aerospace applications for example. What usually matters the most is the cost. It can of course be the manufacturing cost or other cost benefits received with longer lifetime, quicker assembly or savings in processes the component affects. This is the same with flying or moving applications as well but in more traditional applications things tend to be more stationary and thus for example fuel savings received with lightweight design do not necessarily play a role. That is why it is essential to build a solid business case before moving your manufacturing towards AM.

In this presentation we dig into the costs of additive manufacturing and how we can affect them. It is not anymore €/kg of material that makes majority of the costs but instead the used machine time that counts. Reducing support structures will lessen machine time and also reduces time needed in post processing after the printing process. Being able to pack as much as possible of your components on the build plate will also result into smaller amount of machine time per component.

But what if you have already filled the build plate as dense as possible with your components and minimized the need for support structures? Well, then you will move into 3D and start stacking, or nesting, those components to fill up the whole build chamber.

The presentation will cover the basics of costs for AM components to give you an understanding what to look for when designing for AM. A case study is also gone through to elaborate how nesting can affect your components costs, what needs to be taken into account when designing for nestable components and, if this is so fabulous, why is not every component being nested.

FDM Industrial Applications for Production Lines and Low-Volume Manufacturing

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Keywords: 3D printing, industry

Abstract

The use of 3D printing in the world changes from year to year. Through the last 20 years of additive technologies have come out of the R&D laboratories, and they started to go to production, maintenance or even marketing departments.

Support for production processes. 3D printing has entered the companies' production lines. In 2017 22% of them used printouts in the production process, or maintenance.

Customization of products for customers. Customization of products is currently one of the most important trends. Low manufacturing costs for personalized parts open up new possibilities.

Implementation of new products. More than 30% of manufacturing companies using 3D printing technology for the shortening of the development process of a new product.

Proof of concept. The verification of R&D ideas is one of the following the most difficult processes in companies. Additive technologies allow for a low cost verification of whether a product or service will fit the market needs.

Laser Metal Deposition Application as a New Concept of Maintenance According to the Industry 4.0 Idea

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Keywords: LMD, Industry 4.0, part regeneration, Reverse Engineering (RE)

Abstract

Industry 4.0 demands high efficient and totally automated processes. Additive manufacturing and reverse engineering development are crucial for increasing effectiveness in modern industry. They start playing a bigger role in maintenance process. Industry needs solutions which provides continuity of production when some failure would be occurred.

So, there are some installations exposed to unplanned production downtime which is associated with high cost of catastrophic damages and high cost and long delivery time of critical spare parts.

The aim of project was to prepare concept workflow how the idea of application Laser Metal Deposition technology and reverse engineering (using 3D scanner and laser scanner) could influence the maintenance industry sector in Poland. This project was divided on business and technical parts to show potential customers when that solution is profitable. Firstly, Value Proposition Canvas was developed with potential clients in case to prepare tools for solving their problems in maintenance.

From the business point of view, analytical tools have been prepared for the customer to determine the cost-effectiveness of the solution and what resources, data are necessary to prepare job specification.

From the technical point of view, a set of tools needed to complete the task was developed as well as type of devices were selected too. Depending on the problem, type of solution should be considered like LMD process quality, time and place for repair. So, it has been possible to design for client mobile and stationary solution for maintenance in their industry.

On this account, standard process flow was proposed from problem identification, applying reverse engineering to use Laser Metal Deposition technology to part regeneration [1].

To sum up, industrial companies face more and more complex challenges in maintenance and they have to ask for innovative and individually tailored solutions which provide continuity of the work for a reasonable price.

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SESSION 6

AM IMPLEMENTATION

From Powder to Part: Microscopy and Measurement Solutions for Additive Manufacturing

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Keywords: Additive Manufacturing, measurement solutions, microscopy

Abstract

An emerging manufacturing technology, additive manufacturing or AM (also known as 3D printing), is quickly starting to attract interest in both the academic community and the industrial world. Although AM has been around for a while for plastics for prototyping and tooling, in the last 7–10 years there has been a big boom in AM with metal, pushing into new areas of industry and production. AM is now being considered a new revolution in manufacturing and will be a major disruptor.

Modern 3D printing research labs need microscopy for the following reasons: for comparison with properties of conventional manufactured parts, to understand failure mechanisms, non-destructive characterization of the complete part in 3D. Further, it allows an evaluation of severeness and number of defects as well as to decide about region and type of further investigation with high-resolution and chemical methods. Also optimization of CAD models is needed. To bring 3D printing from prototype production to serial production, an analysis of various parameter that are spanning over multiple scales is needed including structural, chemical and 4D evolution studies.

Hearing Instruments Production with DLP Technology. Case Study

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Keywords: Hearing Aids Production, DLP Technology, Additive Manufacturing

Abstract

DGS is an internal function of Demant Group, which supports the operations of all the companies within the group in various business fields. Gathering all the key processes in one place, allowed Demant to conduct their operations more efficiently and focus on providing the highest quality of services.

Over the course of its 10-year existence, the company expanded their production range to technologically advanced hearing aids and diagnostic equipment.

Hearing Aids production can be divided into two basic styles: Behind-the-Ear (BTE) and In-the-Ear (ITE).

The ITE Hearing Aids are almost entirely produced using additive manufacturing technology. Hearing Aids must be customized to fit in the beneficiary's ear, so ITE hearing aids production using additive manufacturing is more comfortable because they perfectly match the wearer's ear.

In the hearing aid production process, DGS Poland performs additive manufacturing with one of the most worldwide recognized technologically advanced 3D printer machines in DLP technology. This allows to radically improve quality of printing process and reduce time needed for that process. Using DLP technology, DGS Poland is able to offer all currently existing color variation taken from 3D resin market.

Due to the dynamic growth, DGS employs almost 3000 people in Poland and is constantly expanding its operations, while continuously hiring new employees.

Currently ongoing strategic projects regarding additive manufacturing technology:

1. 3D printing process optimization – printed details efficiency improvement.
2. Testing and implementation of the newest generation of 3D printers and 3D resin.
3. Optimization of post-processing technology (drying process, curing process and surface finishing).

3D Printed Tooling for Casting of Bulky Epoxy Products

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Keywords: Electrical Insulation, Epoxy Casting, Binder Jetting, Tooling

Abstract

Application of polymeric materials is growing dramatically and thermosetting polymers (epoxy resins and liquid silicone rubbers) are broadly used as main electrical insulation in high voltage electrical products (instrument transformers, bushings, embedded poles, and others). Their common usage in electrical applications is due to superior electrical insulation properties and very good mechanical and chemical resistance offered by these materials. As the manufacturing process a reactive moulding technology is often used, and two methods are popular: vacuum casting and automated pressure gelation (APG). In both cases metallic moulds are used to cast and cure the final products.

Design of appropriate shape and pre-heating system of the moulds used in casting of epoxy materials are essential in respect to proper initiation and propagation of curing fronts that influence the final quality of the cast products. Moreover, very often it is necessary do manufacture the moulds for urgent short-series production, and traditional mould machining is too expensive, and in addition a long awaiting time is not accepted by the customers. Having that in mind a novel approach based on application of additive manufacturing for moulds' fabrication have been investigated.

In the presentation an unique 3D printing – based concept for manufacturing of the moulds used in manufacturing of electrical products with epoxy electrical insulation has been presented focusing on bulky components. The proposed approach involves a sand binder jetting technology allowing very fast manufacturing of complex moulds with high dimensional stability, and what is important for multiple casting purposes. This technology is mainly used in metal casting processes, but here the sand mould is used only once, since after metal solidification it is destroyed. Due to relatively high surface roughness of printed sand, novel concepts for dedicated coatings have been evaluated and tested to achieve robust process and good material integrity. The results of first successful industrial epoxy casting trials have been also presented and the research scope for farther process improvement has been discussed.

Clay Printing – Earth Experiments on Martian Clay Simulant

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Keywords: Clay printing, bionic, g-code, Martian clay simulant, material experiment

Abstract

Presentation of one of the parts of a project titled "In The Rust We Trust" – this stage will concern experiments with MGS-1, which is a Martian clay simulator created in the Exolith Lab laboratory at the University of Central Florida.

The entire project titled "In The Rust We Trust – is a study of structures that are created by micro-civilizations, such as termite nests, anthills or other structural products fount within the natural world. The strategy of project implementation consists in developing and describing the principles of their generation by means of generative algorithms. The next step is combining and modifying them, in order to obtain new bionic structures being a derivative and not a copy thereof, in a dynamic and non-linear way.

Materialization of the experiment will be possible thanks to the use of digital production tools and incremental technologies (clay printing). The designed constructions or common-use objects made with the use of the substitute of Martian clay are to introduce the human aspect into the space existing between the micro and the macro-scale of the cosmos.

The new structures will be its mutations and iterations derived from nature, not its imitation. During the AMM conference, the first documented attempts to implement printouts and burning of the hydrated Mars and regolith substitute will be presented.

In my experiment, I focus on Mars because the most recent discoveries indicate that sedimentary rocks, including clays, and water were found there, which makes it possible for me to carry out a simplified simulation of my experiment. Research work on Martian soil and recreation of the composition of Martian regolith on Earth date back to the Viking lander's times.

MGS-1, otherwise known as Mars Global Simulant, developed in 2018, is the first mineralogically precise simulant of Martian regolith. It is based on materials found in Rocknest soil in Gale crate on Mars, which was extensively analyzed by NASA's Curiosity rover. MSG-1 is obtained by mixing pure minerals in exact proportions, and then combining the minerals and re-grinding in order to obtain precise distribution of the size of particles.

Exolith Lab has published various specifications for the development of simulated soils. They include a modified version of MSG-1 based on the case of hydrated clay based on NASA Mars In-Situ Resource Use research.

The reasonableness of my interest in clay is confirmed by the fact that in December 2018, the Curiosity rover started a new chapter in geology, called 'Clay Bearing Unit' (CBU). Thus, Curiosity changes its location from hematite-rich formations to the region with a large amount of smectites (groups of clay minerals) in the ground. This bottom layer of Mount Sharp, where the rover is located, is the key to understanding environmental changes on Mars.

Designed structures will be implemented with the help of the Silkwarm plugin which transforms the Grasshopper and Rhino geometry into a G code for printing in 3D. The plugin allows full manipulation of G-Code printer, making it possible to determine innovatory properties of printed materials.

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ABSTRACTS OF YOUNG SCIENTISTS POSTER SESSION

The Influence of Part Build Orientation on Its Strength Properties and Dimensional Accuracy in Multi Jet Fusion Technology

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Keywords: Multi Jet Fusion (MJF), PA12, dimensional-shape accuracy, mechanical properties

Abstract

Over last few years the additive manufacturing industry (AM) has been experiencing an extremely high development. Nowadays AM rapidly becomes one of the most important production technologies. One of the newest AM technologies is, developed by Hewlett-Packard, Multi Jet Fusion process (MJF). The purpose of this paper is to evaluate and benchmark mechanical strength and dimensional-shape accuracy of parts manufactured by a MJF according to the part build orientation in the printing chamber. The material used in the study was polyamide 12 (PA12) which is one of the most commonly used material in additive manufacturing. The elements were printed using the balanced program mode, which provides sustainable properties of the final product.

For the purpose of this paper twelve objects were manufactured. The dimensional-shape accuracy was checked with linear scanner RS3 integrated with Romer Absolute Arm 75201SI. The surface roughness was examined according to ISO 25178 standard by non-contact profilometer. The macro and micro structure of the printed objects, as well as part porosity were examined by light and SEM microscopy as well. For the purpose of the mechanical properties testing, the samples were printed directly with the dimensions mentioned in the standards. The tensile strength was investigated in accordance with ISO 527–1. The Charpy's impact strength tests were carried out in accordance with ISO 179 and the flexural strength measurements were conducted according to ISO 178.

Anodic Oxidation of AlSi10Mg Alloy Manufactured by DMLS

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Keywords: DMLS, electrochemical oxidation, anodizing, aluminum alloy, AlSi10Mg

Abstract

Direct Metal Laser Sintering is a powder bed fusion process, which allows direct production of elements with complex shapes and very good mechanical properties. However, regardless of manufacturing technology elimination of some materials' weaknesses is definitely tough to eliminate. These weaknesses might be excluded by surface engineering.

This poster presents results of producing oxidized films on AlSi10Mg alloy manufactured by Direct Metal Laser Sintering using EOSM280 system equipped with 400W Yb fiber laser [1] and standard EOS AlSi10Mg powder [2]. AlSi10Mg is a near-eutectic die casting alloy which is applied to automotive and aviation industries [1, 3]. The density of printed samples was under 99%. We used 3 different methods of oxidation: traditional electrochemical oxidation, electrochemical oxidation in lower temperature (hard anodizing) and plasma electrochemical oxidation. Processes lasted 20 or 25 minutes. Traditional and hard anodizing was carried out in H_2SO_4 with the voltage in the range of 18.5–32.5 V. Plasma oxidation was carried out in 2 g/l KOH + 4 g/l Na_2SiO_3 and the applied voltage was between 190 and 225 V.

Metallography, SEM and EDS proved that we received Al_2O_3 oxides on the AlSi10Mg surfaces. All produced films were thin (2–5 μm), providing slightly increased microhardness and roughness of the surface. Roughness depends especially on electric current parameters applied in the oxidation process. Therefore the structure of layers manufactured by plasma electrochemical oxidation was more irregular and porous. All films had high adhesion which was confirmed by scratch tests.

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Chemical and Electrochemical Polishing of 3D Printed Metal Parts

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Keywords: Selective Laser Melting (SLM), Titanium alloy, Nickel-based alloy, chemical polishing, electrochemical polishing

Abstract

In recent years, Additive Manufacturing (AM) has become a mainstream manufacturing technology. 3D printing of metal parts is of particular interest to the aerospace and biomedical device industries, especially where the ability to manufacture low-volume, complexly-shaped parts with fine structures and gradient mechanical properties are desirable. Despite the rapid growth and wide interest in 3D metal printing, there are still many challenges related to developing reliable additive manufacturing processes.

As manufacturers of medical and aerospace devices consider AM, they must also consider how to obtain sufficient rendering accuracy and surface quality. Due to the nature of AM, unmelted powder particles become attached to each part's outer surface. In order to obtain the required surface finish, those particles must be removed by postprocessing methods. This becomes especially challenging on the surface of complexly-shaped parts, especially where those complex shapes are closely-packed truss structures or channels. These areas are effectively "porous" regions. The mechanical post processing methods most commonly used to remove particles is blasting. However, this technique is likely to be insufficiently effective in porous regions. Therefore, chemical and electrochemical polishing methods are often explored. In those polishing methods, the manufactured part is often immersed in an acidic solution which dissolves the connections the unmelted powder particles have to the surface. Depending on the material, different reagents mixtures, as well as concentrations of reagents, can be studied. The process can be also dependent on part size and geometry. Thus, all else being equal, post-fabrication processing parameters to remove unmelted, but attached, powder particles (i.e., polishing parameters) may need to be determined separately for each part geometry. In this study chemical and electrochemical polishing for 3D printed titanium and its alloys, including nickel-based alloys, were studied. For each material, different reagents and concentrations were selected and investigated. As a result proper solutions, HF-HNO_3 for titanium alloy and H_2SO_4-methanol for nickel-based alloy, were determined in regard to obtaining the best surface quality as well as fabrication that is accurate to the original CAD dimensions of the part.

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Effect of Interpass Temperature on the Properties of Al-Cu Alloys Parts Produced by Wire and Arc Additive Manufacturing

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Keywords: Wire Arc Additive Manufacturing, GMAW, Al-Cu alloys, microstructure

Abstract

Metal additive manufacturing (MAM) is currently used in industries such as aeronautics, automotive, aerospace, medical, among other sectors, due to the advantages of this technology over traditional manufacturing processes. The complex and the geometry-optimized components, which can be built by additive manufacturing, are part of the driving force to the development in this area. Among the main methods used in MAM, those based on wire and arc welding stands out because of the high deposition rates achieved, lower operation costs, and more efficient use of raw materials. The Al-Cu alloys have been extensively used in aeronautic and automotive industry due to the high mechanical strength achieved with this material, mainly due to precipitation hardening, low specific density, and good corrosion resistance.

In this study, various deposition strategies were under consideration, such as the cooling of the substrate and control of interpass temperature for wire and arc MAM parts. The effect of those strategies on the microstructure evolution, mechanical properties and integrity of the produced parts was assessed. The parts were evaluated by optical and scanning electron microscopy, hardness, and tensile tests. The results show the influence of the interpass temperature on the microstructure, mechanical properties, dimensional control of the beads as well as the surface appearance of the manufactured part.

Thus, with fine-tuning and adequate optimization of the experimental process parameters of the wire arc additive manufacturing setup the analyzed parts could have their mechanical characteristics improved. MAM using wire arc has great potential and capability to substitute or be used together with traditional manufacturing technologies, enhancing the final properties of the materials.

Methodology of Powder Qualification for L-PBF Process on Example of Nickel-based Alloy IN718

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Keywords: SLM, L-PBF, IN718, powder characterization, material characterization

Abstract

The quality of metal powder is important to ensure consistent production of parts via laser bed powder fusion process (L-PBF). In general it is assumed that metal powders for AM use should be nominally spherical, must be characterized by an appropriate fraction size distribution that is optimized for volume density (Hausner Ratio) and be adapted to the processing capabilities of the electromagnetic radiation beam [1]. Other features include morphology, density, chemical composition and flowability [2]. The most important properties of AM powders and its measurements methods are presented in Table 1.

Table 1. Important properties of metal powders in the context of AM application and its measurement methods

Analised property	Measuring method	Standard
The size distribution of the powder fraction	Laser diffraction / Sieve analysis	ASTM B822 / ASTM B214
Bulk density	Hausner Ratio / Carr index	ASTM B213 / ASTM B527
Powder flowability	Hall Flow funnel / Rotary analysis	ASTM B212 / n/a
Powder size and morphology	Computed Tomography / SEM	n/a
Chemical composition of the powder	EDS, Extraction, other	Accredited measurements
Crystalline phases of powder particles	X-ray diffraction	PN-EN 13925–1:2007
Absorptivity	Ulbricht Sphere	n/a

These properties affect the final mechanical and physical properties of the manufactured elements (flowability, bulk density, fraction size) as well as affect the stability of the manufacturing process (absorbance, reflectivity). As a part of the study, measurements methodology were described, examined and discussed. Properties of Inconel 718 powders were than measured and used as an example.

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Influence of Active Pharmaceutical Ingredients and Plasticizers on Processability of HPMC with FFF Technology

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Keywords: HME, FFF, FDM, HPMC, API

Abstract

Presented study's objective was to examine influence of active pharmaceutical ingredients (API) and plasticizers of processability of Hypromellose (HMPC) in Hot Melt Extrusion and Fused Filament Fabrication (FFF). Evaluation is a basis for the selection of HPMC grade and its possible mixtures with API and plasticizers which will be possible to produce "3D tablets" using additive manufacturing technology. HME is manufacturing method which is getting attention from researchers for preparation of novel drug delivery systems, which allows to prepare solid dispersions, that are especially recommended for poorly water-soluble drugs or controlled release formulations [1–3]. However high glass transition temperatures (in rage of 160°C to 210°C) in connection to low degradation temperature (in range of 200°C to 250°C) and its high viscosity makes the HPMC polymers challenging to process using HME [4]. In this case HME is a method for preparation of batch material for FFF, so called filament. Similar mechanism of processing conditions of both technologies and higher processing temperatures in FFF then HME demand proper preparation of the batch material for proposed additive manufacturing technology.

Polymer, plasticizers, API and its mixtures was prepared and analyzed using Thermogravimetric analysis, Differential scanning calorimetry. For each blend Melt Flow Index was determined. Extrudates were subjected to a hardness test, evaluated if material is not too soft to be processed. Results were compared to commercial PLA, which is one of the most popular material processed with FFF technology.

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Application of Alloys Based on Ternary Ti-Nb-Zr System in Additive Manufacturing – Review

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Keywords: β-titanium alloys, SLM, scaffold structures, biomaterials

Abstract

The most popular titanium alloy in implantology is Ti-6Al-4V, which contains chemical elements that cause negative neurological reactions or toxicity in the environment of human tissues. These effects can cause a delay in osteointegration processes after implantation. In addition, this alloy is characterized by a higher elasticity modulus (110 GPa), compared to cortical bone (10–30 GPa), causing bone tissue resorption as a result of stress shielding [1].

New generation titanium alloys, in particular, the series of β-titanium alloys based on the ternary Ti-Nb-Zr system, are successfully developed and implemented as biomedical material [1,2]. These alloys have an elastic modulus, depending on the percentage of alloying elements, in the range of 40–80 GPa, which is crucial due to the fitment of mechanical properties [3]. In addition, these alloys are characterized by superior corrosion resistance in the environment of any human body fluids, due to the high stability of niobium oxide [3].

SLM technology is a promising method for the production of implantological structures, in particular, scaffold structures using Ti-Zr-Nb alloys, due to the mimic of mechanical properties and architecture of bone tissue. With SLM technology, there were successfully processed e.g. Ti-13Nb-13Zr alloy to obtain scaffold structures [5], Ti-21Nb-17Zr alloy for the production of elements for prosthetic applications [6], Ti-35Zr-28Nb alloy also for the manufacturing of scaffold structures for applications in biomedical engineering [4].

SLM-processed Ti-Zr-Nb alloys, due to their high corrosion resistance, biocompatibility as well as adequate mechanical properties, show promising potential as materials for hard tissue implantation or customized medical devices for applications in dentistry.

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The Influence of Abrasive Blasting Parameters on Surface Quality of Titanium Alloy Ti-6Al-4V Parts Produced by Electron Beam Melting

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Keywords: EBM, Ti6Al4V, sand blasting, mechanical characterization

Abstract

Additive manufacturing (AM) includes a wide range of technologies which allow to build up object layer by layer and offer enormous opportunities in the field of production of objects based on CAD data. One of the representative of AM technologies used to produce metallic parts is Electron Beam Melting (EBM). This process offers ability to fabricate light-weight or near net shape elements with complex and customized shape. EBM is appropriate also for materials with a high affinity for oxygen like titanium alloys e.g. Ti-6Al-4V [1–3].

Obtaining satisfactory dimensional- shape accuracy and surface quality are significant limitations of AM. The surface quality obtained by EBM is lower compared to traditional manufacturing processes, such as machining. The surface roughness of the EBM parts depend on the material, process parameters and need of use supporting structures. The surface quality is also strongly influenced by the so-called "stair" effect, which results from the approximation of curves and inclined surfaces by layers. This effect occurs in all AM processes as a consequence of layered manufacturing.

Parts directly after the EBM process are characterized by high roughness (Ra 40–50 µm). Surface quality influence on decreasing of strength properties by the reduction of the effective cross-section, which changes the mechanical properties [4] and can causes premature damage of the parts. This is one of the reasons why EBM parts always need surface post processing treatment [4]. One of the methods to improve the surface quality is abrasive blasting. Depending on abrasive material, pressure and time it is possible to obtain different results in term of surface quality and therefore mechanical properties.

In particular, the study considers specimens produced by EBM process and then sand blasted with various combinations of parameters (time, pressure), in order to control the impact of abrasive stream on the surface of Ti-6Al-4V and comprehensively investigate how it correlate with surface and mechanical properties.

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Manufacturing of Ti-Nb Alloy from Elemental Powders by EBM

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Keywords: EBM, Titanium alloy, material characterization

Abstract

Ti-based alloys are widely investigated nowadays for biomedical implant manufacturing. For such applications, the alloys should be biocompatible as well as possess low elastic modulus, to avoid the stress shielding effect that appears when high modulus metallic implants are inserted into low modulus bones. It was proved that titanium β phase has a lower modulus than that of the α phase, therefore the β phase is more effective in avoiding mismatch in modulus between the implant and adjacent bones [1]. Nb is one of the β-stabilizing elements and has an important influence on the phase transformation in Ti-Nb alloys by completely dissolving in β-Ti and forming β (Ti, Nb) solid solutions [2]. The elastic modulus of Ti-Nb alloys manufactured by Fischer *et. al.* by selective laser melting (SLM) from mixture of Ti and Nb elemental powders was about 77 GPa [3]. To our knowledge, Ti-Nb alloys were firstly manufactured with electron beam melting (EBM) using a mixture of Ti and Nb elemental powders by our research group. The objective was to investigate the microstructural and mechanical properties of the obtained alloy. For this purpose, non-spherical niobium and spherical titanium powders were mixed with different weight proportions. They were melted with the electron beam melting process with different parameters, impacting the global energy delivered to the surface.

The microstructures of the obtained Ti-Nb alloys were investigated by X-ray diffraction analysis (XRD). The size of grains and melt pool depth were measured by scanning electron analysis (SEM). Corrosion analysis was also explored. X-ray computed tomography (CT) was conducted to investigate the size and amount of unmolten Nb particles in bulk specimens depending on area energy input. Mechanical properties were investigated using in-situ uniaxial compression testing, in combination with digital volume correlation (DVC).

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The Influence of Various WAAM Parameters on the Microstructure of Cu-Al Alloys

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Keywords: WAAM, microstructure, additive manufacturing, copper alloys

Abstract

The results of the investigations on the microstructure and hardness of Cu-Al alloys are presented. The Wire Arc Additive Manufacturing (WAAM) process, which belongs to the additive manufacturing (3D printing) techniques, is considered as very promising technique for manufacturing of a wide range of products compared to conventional technologies. The WAAM process uses metal wires as a feedstock material and also an electric arc heating source equipped with a wire feeding system to manufacture elements by building them up, layer-by-layer. Using existing welding equipment makes it much cheaper compared to other additive manufacturing technologies, e.g. which utilize powders [1]. Moreover, advantages of this technology are low porosity of final elements, manufacturing of complex-shape products and reducing the post production treatment. The degree of the porosity depends on WAAM process parameters, such as melting temperature, wire-feed rate, welding speed, etc. A multitude of these factors require carrying out extensive investigations on effects of the process parameters such as deposition patterns and sequences, cooling or preheating on the microstructure evolution [2]. The results of the microscopy investigations as well as hardness of the Cu-Al type alloys printed out by means of 3DMP® process with different parameters are shown.

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Analysis of Fused Filament Fabrication Strategy on Polyamide Properties

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Keywords: FFF/FDM, PA12, nylon, material properties

Abstract

Polyamide (PA, Nylon) has good mechanical properties, good strength and wear resistance as well as low friction coefficient. PA is applied in many branches like automotive, electrotechnics, electronics, aviation and packaging. Additive Manufacturing techniques use polyamide as working material since SLS or MJF methods were introduced. Currently also FFF (Fused Filament Fabrication) enables manufacturing PA parts.

Influence of Fused Filament Fabrication strategies on polyamide properties are presented and discussed in paper. Variable parameters were: infill structure, infill ratio and sample orientation in FFF machine workspace. Filament from 5 independent producers was used. Samples with infill ratio of 60, 80 and 100% were manufactured. Inner structure was diagonal or honeycomb. Samples were oriented in relation to building plate with angles of 0, 45 and 90°. Reference samples were manufactured by injection moulding.

Then standard tensile strength tests were applied. Results show clearly that 0° angle was optimal, considering tensile strength. However it is obvious, results for different angles – corresponding to variable AM geometry show interesting phenomena. Best Young modulus for solid infill observed in samples manufactured also with zero angle. Other angles caused lower tensile strength parameters but one could foresee influence of angle on parts properties. Inners structure type was less significant (differences between cross and honeycomb structures were approximately 10%). Considering however structure in relation to infill ratio observed that better and more stable parameters were achieved by application of honeycomb infill. Generally results were comparable to reference samples. It should be underlined that the aim of this research was to compare materials from different manufacturers in different configuration. Results enabled to select producers of materials with optimal characteristics for manufacturing series of prototypes for tele-rehabilitation device cases. Concluding only 2 manufacturers of PA12 filament fulfil requirements of tensile strength parameters.

Application of the 3DMP® Technology in a Marine Industry

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Keywords: Additive Manufacturing, WAAM, marine industry, copper alloys, renewable sources

Abstract

The constantly increasing demand for new, environmentally friendly and sustainable technologies enabling the production of innovative components, including those intended for devices used in the marine equipment sector, were the inspiration to begin the research on development of the new Cu based alloys and a production process by means of 3DMP® technology [1]. The 3D Metal Printing (3DMP®) technology belongs to the Wire Arc Additive Manufacturing (WAAM) group technologies but was improved and patented by Gefertec (project Task Partner). The 3DMP® process which uses a metal filler wire as a feedstock material is a suitable technology to manufacture products of very high strength (durability), internal structure free from defects and resistance to the aggressive corrosion of seawater as well as high wear resistant. One should also emphasize that 3DMP® technology enables to build constructions and equipment of lower weight in comparison with the products presently available on the market at lower material loss. Moreover, 3DMP® technology is an alternative for techniques which utilize metal powders, especially in manufacturing large elements [2].

The project will result in a ready to implement 3DMP® technology for manufacturing of corrosion resistant components and achievement of the objective of the project will contribute to the development of devices used in obtaining energy from renewable sources as well as marine equipment. On the other hand, implementation of the newly developed technology will allow to significantly reduce the amount of production wastes, consumption of Cu and energy consumption during production as well as negative impact on the environment.

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Development of Manufacturing Method of the MAP21 Magnesium Alloy Prepared by Selective Laser Melting (SLM)

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Keywords: SLM, MAP21, Magnesium alloy, material characterization, processing parameters

Abstract

Magnesium alloys are well known of its biocompatibility and biodegradable properties [1], [2] owing to the fact that magnesium is crucial mineral for human body, especially bone tissue. There are studies [3] on using WE43 additively manufactured magnesium scaffolds for full bony and soft tissue regeneration. Moreover, magnesium implants in bones were investigated as having higher bone-implant interface strength than titanium ones [4].

This paper presents the results of the studies on MAP21 magnesium powder selective laser melting process optimization as a starting point for further bioapplications. MAP21 magnesium alloy owing to its high mechanical properties, excellent vibration damping characteristic and good creep resistance is a promising material to be tested for scaffold structures. Using an algorithm based on design of experiment (DoE) method [5] the SLM process parameters were designated. The porosity was investigated by optical microscopy as an optimization parameter. Microstructure and oxidation level after selective laser melting (SLM) manufacturing were characterized by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). In order to determine the mechanical properties of MAP21 alloy processed with SLM technology, static tensile test and microhardness test were carried out. The study shows for the first time successful SLM manufacturing of dense samples made of MAP21 alloy.

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Effect of Powder Properties on Mechanical and Physical Properties of Ti64 Processed by SLM

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Keywords: SLM, Ti64, Titanium alloy, material characterization, powder properties

Abstract

It is commonly known that powder properties, such as grain size distribution, sphericity and chemical composition, influence the material properties of parts produced by powder bed based additive manufacturing processes such as selective laser melting (SLM). [1], [2], [3].

In scope of this work three differently produced powders of the titanium alloy Ti6Al4V are tested on their physical and chemical properties as well as their influence on build results.

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Cascaded Optical Fiber Sensor for Temperature and Strain Monitoring of 3D Additive Manufacturing Processes

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Keywords: Additive Manufacturing, embedded fiber sensors, real time monitoring

Abstract

Fiber optic sensors has been recently proposed on detection of defects in additive manufacturing (AM) systems. There are many advantages associated with the fiber sensors technology, such as reduced dimensions, chemical inertness, multiplexing capability, nearly punctual operation, and possibility to measure different parameters within one single optical fiber. Regarding the specific application for AM processes, these sensors can simultaneously measure temperature and strain induced [1].

Fiber Bragg grating (FBG) sensors have represented the most promising solutions to characterize AM based composite products. However, as these sensors are sensitive to more than one physical parameter at the same time, such as strain and temperature, they suffer large cross sensitivity [2]. The most common method to simultaneously discriminate strain and temperature, is using two different fibers with an FBG in each one: one strain-free FBG (involved by a capillary) for temperature sensing and another one for detecting strain and temperature, simultaneously. However, when it is intended to embed in materials, this method is not adequate because it increases the invasiveness and a punctual discrimination is not performed [3].

Fabry–Perot (FP) interferometer sensors based on air cavities are also typically used to monitor strain variations, since they are almost insensitive to temperature shifts. However, as FBG sensors, when they are embedded in materials, their sensitivities to temperature and strain changes due to mechanical stresses produced by the surrounding materials, requiring always an internal calibration [3].

Internal discrimination of strain and temperature in composite materials can be improved by combining the signals of FBG and FP, by writing the FBG sensor as near as possible to the FP cavity, performing a cascaded optical fiber sensor. This sensing methodology decreases the intrusiveness and allows a simultaneously and punctual monitorization.

In this study, a cascaded optical fiber sensor was embedded during the Fused Deposition Modeling 3D printing process of a polymeric matrix (PLA) reinforced by a NiTi strip. The objective was to discriminate and perform real-time monitoring of internal temperature and strain shifts. The experimental results shown the good adhesion of the cascaded optical sensor to the surrounding material, where a consistent deviation of temperature between the external face of the PLA matrix (measured by thermography) and 2 mm up down (where the sensor was placed) can be observed, and due to the PLA accommodation, a successive contraction of the PLA matrix after the heating/cooling cycles occurs.

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Mechanical Properties and Structure Analysis of PLA Bone Regeneration Scaffolds Manufactured with the Use of FFF Method

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Keywords: Personalized medicine, scaffolds, biopolymers, Additive Manufacturing, FFF

Abstract

Bone regeneration scaffolds is an area of knowledge that is developing rapidly due to new technologies and materials introduction. Nevertheless combination of those two is only successful when proper research, oriented on expected scaffold function, is conducted.

The aim of this study was to establish connection between the geometry of the polymer scaffolds, the technological parameters used within manufacturing process and mechanical properties, which is very important in the case of tissue damage, where assurance of needed support of scaffold structures is crucial for osteogenic processes. Cylindrical samples were manufactured using Fused Filament Fabrication method (FFF) with a set of various process parameters, from biocompatible PLA (Polylactide) material. The internal structure was inspected with the use of Computed Tomography (CT), this allowed to determine the relationship between the obtained scaffolding geometry and technological parameters. The mechanical properties were determined under compression test, based on the obtained stress-strain curves, maximum strength, Young's modulus and maximum strain were calculated (Fig. 1).

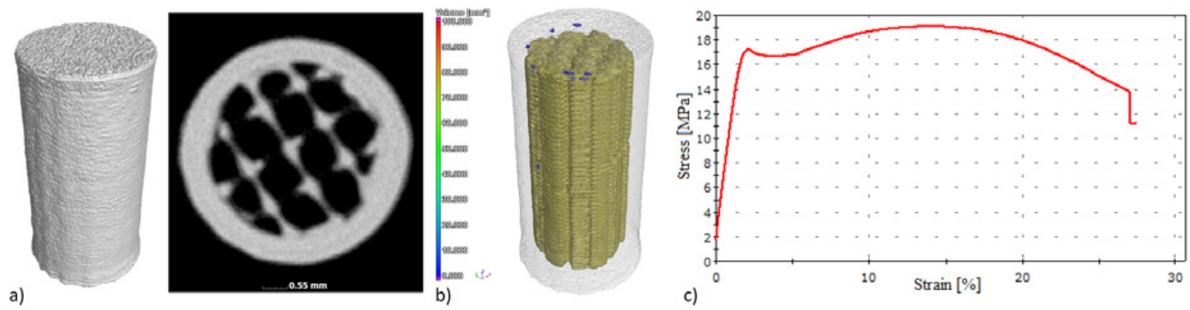

Fig. 1a), b) The result of CT reconstruction – 2D and 3D view, c) Stress-strain curve

As a result of the research, a parametric model was developed that allows the theoretical determination of porosity depending on the process variable parameters used. In addition, the ability to control mechanical properties depending on the selected process parameters and the achieved internal porosity was indicated.

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The Designing Process of Personalized Products Based on Reverse Engineering Tools on the Example of an Intervertebral Disc Implant

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Keywords: Reverse Engineering, Additive Manufacturing, personalized implant, cervical spine

Abstract

Reverse Engineering (RE) is a process based on information obtained from a physical product, its analysis and processing, which leads to the creation of a new product, often in an improved form [1]. RE tools are used in medicine, where input data in the form of CT or MRI images, enable the development of implant geometry dedicated to a specific patient.

Additive manufacturing (AM) is a technology which is widely used for the production of individualized implants that can perfectly replace damaged tissues. Due to the possibility of modelling various shapes AM is an ideal method allowing to obtaining the optimal shape of implants and prostheses.

The aim of this study was to present the designing process of a personalized artificial intervertebral disc implant placed between the C3/4 levels in the cervical spine. Described process is presented in Figure 1. Based on CT data (Fig. 1a), cervical vertebrae geometry was prepared. Subsequently, the initial implant geometry was developed on this basis (Fig. 1b). Afterwards, two designed models of implants were verified using the numerical methods FEM. Two types of material containing titanium were selected for simulation test: Ti6Al4V and Ti13Zr13Nb [2]. Both materials met the strength requirements, but for further tests, due to better biocompatibility and lack of toxic vanadium, titanium alloy Ti13Zr13Nb was chosen. As a result of the analysis, one of the developed models was rejected due to unsatisfactory mechanical parameters. The maximum stresses for the correct implant geometry were at the level of 41 MPa, with maximum deformations amounting 0.013 mm (Fig. 1c).

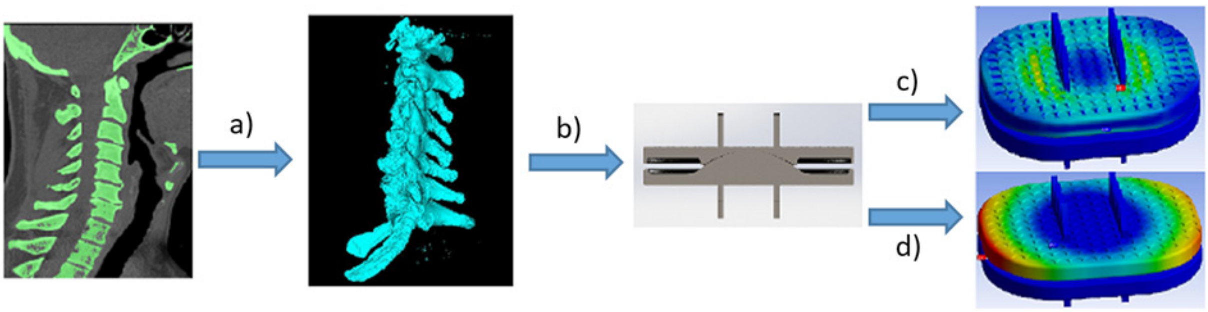

Fig. 1. The process of designing personalized product: a) obtain the geometry of vertebrae, b) modeling the implant geometry, c) maximum strength in the FEM simulation, d) maximum deformations in the FEM simulation

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Function Integration Impact on Failure Rates in Additive Manufactured Parts

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Keywords: Reliability, DFR, PCR, function integration

Abstract

The paper present study of function integration impact on final product failure rate manufactured with utilization of additive manufacturing (AM) technology. Function integration is realized with Part Count Reduction Process (PCR) performed in accordance to ISO 52910 [5] – Additive Manufacturing Design Requirements with additional step for component reliability optimization.

Development of Additive Manufacturing (AM) grants a new portion of flexibility for PCR that can enforce removing assembly connection that secure risk separation. The study investigates AM capabilities in transport applications measuring the impact of part consolidation on system reliability while keeping system functionality. Based model was defined as collection of functions that are realized by components of assembly. Final AM assembly gain reliability improvement with improved AM part characteristic and due to part merge, that eliminates function (and consequently failures modes) required for assembling only.

Comparison of reliability metrics for ISO 52910 complied assembly options proved that additional reliability gain can be achieved with making right decision with Design for Reliability tools during PCR process.

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The Influence of Surface Modification Processes of Additive Manufactured Titanium Alloys on Cytotoxicity and Bacterial Activity

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Keywords: Additive Manufacturing, EBM, Ti6Al4V ELI, surface modification, biofilm, SEM

Abstract

Additive manufacturing allows forming individualized implants that can perfectly mimic the anatomical structure. Implantation efficiency depends not only on the functional or mechanical properties of the implant but also on the surface properties. Objects manufactured using Powder Bed Fusion technology, such as Selective Laser Melting or Electron Beam Melting are characterized by high roughness. Their surface topography is a consequence of the presence of partially molten and stuck powder particles. The rough surface adversely affects the interaction between the implant and the surrounding tissues. Surfaces showing random topographies (e.g. acid-etched, sandblasted) improve cell adhesion. Therefore, each change in the roughness parameter can have profound consequences on cell growth and proliferation [1–2].

The aim of the presented research was to assess the impact of surface roughness of Ti6Al4V ELI alloy pellets produced using EBM technology and subjected to various surface modification processes such as mechanical polishing, sandblasting and acid-polishing (Fig. 1) on the cytotoxicity and the wettability affecting the ability to form bacterial biofilm.

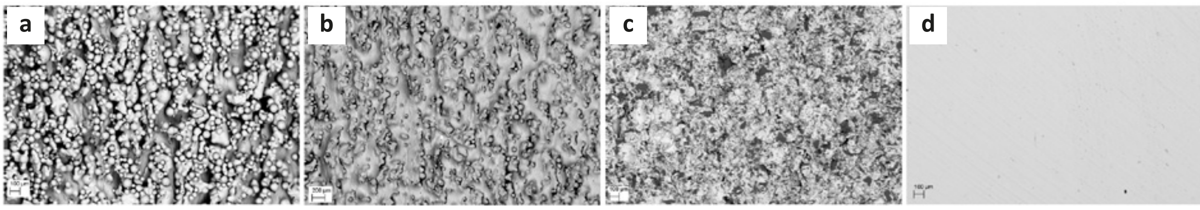

Fig.1. The result of surface modification processes: a) as build, b) acid-etched, c) sandblasted, d) machined, SEM

The prepared samples were subjected to microbiological tests using Gram-positive bacteria cultures. The quantitative microbiological tests were confirmed by visualization of bacterial cells using electron microscopy. To verify the degree of cytotoxicity of the used surface modification methods, *in vitro* tests with the osteoblasts and fibroblasts were carried out. Provided data can be useful for the medical applications of the EBM technology.

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Mechanical Properties of HPMC for Drug Delivery Systems Manufactured Using FFF Process

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Keywords: HPMC, material characterization, FFF

Abstract

Hydroxypropyl methylcellulose (HPMC) is widely used for pharmaceutical and food preparations. The material have been used as coating polymer, bioadhesive, in solid dispersion to enhance solubility, in solid dispersion to enhance drug solubility and as a binder. One other notable use is in the production of capsule shells, replacing the animal derived gelatin in conventional two-piece capsules [1], [2]. The aim of the study was a comparison of HPMC mechanical properties before and after vacuum drying. Standardized test specimens were produced in the injection molding process and divided into two groups one of which has been subjected to the drying process, and indexed as $HPMC_{dry}$.

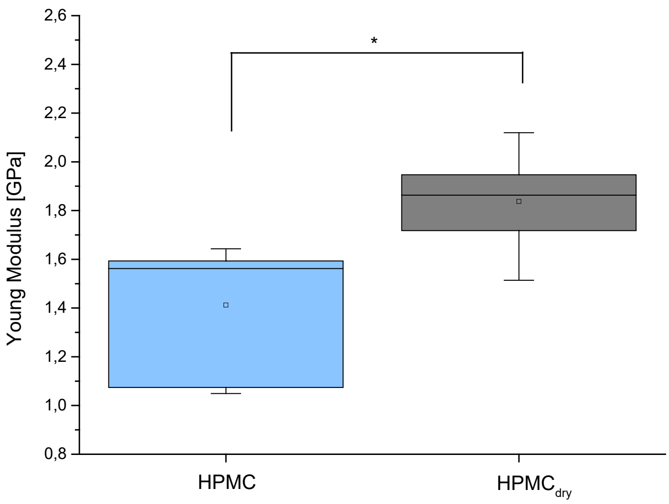

Fig. 1. Young modulus of non-dry and dried HPMC, *$p < 0.05$

The mechanical properties were determined in tensile test, based on the obtained stress-strain curves, tensile strength and Young's modulus (Fig. 1), stiffness and maximum elongation were calculated. Obtained results have shown statistically significant higher values of Young modulus and stiffness of dry HPMC. However the drying process reduces the maximum elongation by half which reaches the value of 0.65% and 1.0% for dried and non-dried material respectively.

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In Situ X-ray Computed Tomography Method for Structure and Mechanical Properties Analysis of Additive Manufactured Polymers

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Keywords: Additive Manufacturing (AM), mechanical properties, Computed Tomography (CT), polymers

Abstract

Additive Manufacturing is widely used for many industrial applications. The use of AM offers many possibilities, but also disadvantages, which we are able to detect more easily using new test methods.

The mechanical properties of polymers especially with complex internal geometry manufactured using additive technologies is an extremely complex issue [1]. Due to the complexity of the problem, standard strength tests are not able to provide us with sufficient data on changes in the internal structure of the tested samples. For this purpose, a specially designed strength machine was used that was placed inside the computer tomography. This solution allows to observe a number of phenomena occurring inside the tested sample. The data obtained in this manner can be used to carry out MES analysis at the product design stage.

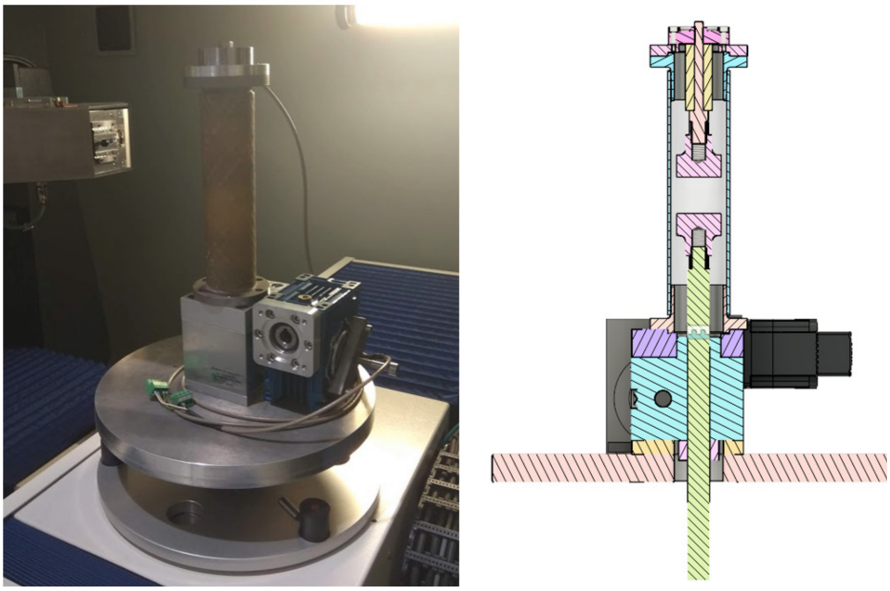

Fig. 1. Test device concept: adjustment in the CT (left) and scheme (right).

Acknowledgments: This work was supported by the Statutory Grant of Wroclaw University of Science and Technology (Grant No. 0402/0074/18).

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3D Printing of Endless Fiber-Reinforced Components

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Keywords: 3D printing, composites, Rapid Prototyping (RP), endless fiber reinforced materials, fiber reinforced 3D print

Abstract

The FFF process does not exploit the full potential of the materials in use, such as PLA or ABS, since mechanical strength is lower in the vertical direction; Therefore, it was investigated how the FFF-3D printing could be improved by freeform printing and with endless fibers. A method has been developed to integrate endless fibers into the thermoplastic matrix of ABS and test these samples afterwards. The samples were composed of three different fiber materials, specifically glass, aramid and carbon fibers, and two different prestressing forces. In order to check the mechanical strength of the samples, tensile tests and fiber pull out tests were performed. The results clearly show that an enormous increase in the tensile strength of the samples can be achieved with the endless fiber reinforced parts. The samples with the aramid fibers were able to absorb the highest forces, as these achieved the highest bonding to the ABS thermoplastic. This could also be confirmed with the fiber pull out tests.

Mechanical Properties, Microstructure and Cell Behavior of CP Titanium Processed by Selective Laser Melting (SLM)

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Keywords: Selective Laser Melting, SEM, STEM, commercially pure titanium (CPTi), microstructure, mechanical properties, solid solution strengthening, cell behavior

Abstract

The aim of this study was characterization of microstructure, mechanical properties and cell response of technically pure titanium (CP Ti) processed by Selective Laser Melting (SLM) in a regulated atmosphere with a slight addition of oxygen (0.2 – 0.4 vol. %) to enhance the mechanical properties of the material. Mechanical tests and microstructure characterization was performed on solid samples while cell behavior tests on scaffolds for bone tissue engineering. This work is one of the first extensive microscopic and microtomography (μ-CT) studies of influence of SLM process on properties of printed solid and cellular structures. The tested samples had a density close to the theoretical density of titanium (~99.0%) and oxygen content in range 0.27–0.50 wt. %. Observations carried out by the light and scanning electron microscopes revealed some micropores typical for laser melting processes. The range of the tensile strength of the tested solid specimens was between 690–830 MPa in the XY plane, and 640–740 MPa in the XZ plane. The maximum elongation at brake showed high anisotropy, and was in range of 16–22% and 8–12% for the XY and XZ planes, respectively. The determined mechanical properties exceed those found in many titanium alloys obtained conventionally. The Young's modulus of the fabricated cellular structures was of 42.7 and 13.3 GPa for as made and chemically-treated scaffolds respectively. These values are very similar to the Young's modulus of living human bone. The confocal and SEM study showed also that in vitro cell performance can be controlled to certain extent by varying the pore sizes in cellular structures. Chemical treatment did not affect negatively cell proliferation and differentiation. Additionally, the chemically-treated scaffolds had a twofold increase in colonization of osteoblast cells migrating out of multicellular spheroids. Furthermore, X-ray computed microtomography confirmed that chemically treated scaffolds met the dimensions originally set in the CAD models. Additional STEM study allowed to determine the lattice parameters of the Ti-α hexagonal phase composing martensitic type of microstructure.

The Temperature Distribution and Thermal Cycles During the 316L Stainless Steel Manufacturing by Laser Engineered Net Shaping

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Keywords: 316L stainless steel, thermal cycles, LENS, material characterization

Abstract

The distribution of temperature and thermal cycles during manufacturing the 316L stainless steel by LENS technique was presented in this paper. 316L stainless steel due to its excellent corrosive resistance is one of the most widely applied material in industries as well as biomaterial for medical applications [1–2]. The LENS technique is a new additive manufacturing method that allows the direct production of metal components by conjunction of a metal powders melting process with pre-designed three-dimensional CAD models [3]. In these techniques a powder is fed directly into the focused laser beam region, resulting in the melting and applying the layer by layer, until the predetermined geometry of the workpiece is achieved. The LENS system, with a focused IPG YLR-500 laser beam, was used to produce the crack-free, full dense bulk specimens from a 316L austenitic stainless steel powder.

During the building of samples with different process parameters, the temperature in solid sample (deposited material) was recorded using the OPTRIS PI 400 thermal imaging camera. The temperature distribution and thermal cycles were determined by using PIX Connect software. Moreover, the temperature distribution in melt pool during the LENS process was also determined using the second thermal imaging camera and the ThermaViz software.

Analyzed temperature distribution allow to estimate the cooling rate during both the solidification and in solid state. Furthermore, during the laser additive manufacturing the thermal cycles are present, which lead to phase transformations in solid state.

Effect of those cycles on microstructure was observed by means of scanning electron microscope (SEM) equipped with an electron backscatter diffraction (EBSD) system and an energy dispersive spectroscopy (EDS) chemical composition analyzer.

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