



Dissertation

Master in Product Design Engineering

***Expanding the limits of Design by Powder Bed
Additive manufacturing based on Digital Selective
Powder Deposition***

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Dedication

This master's thesis is dedicated to my family. My parents Nelson Tavares de Pinho and Marise Borges de Melo Tavares who always supported me in the actions and decisions that I made. In addition, a special mention to my sister, who inspires me to keep going improving my qualities concerning strength, character and knowledge everyday.

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Abstract

In order to develop better concepts and parameters for industrial production processes, an analysis of the engineering and design concepts applied in the sphere of additive manufacturing methods was elaborated. Focusing on Powder Bed technology, this work presents results of experiments derived from Selective Powder Deposition, using approaches for study, assistance and optimization of the influencing parameters in the process and results of the produced parts. Exploring subjects as sintering temperature, agglutination rate, densification process among others, adding these concepts in ceramics and minerals materials.

Keywords: (*Technologies, Additive, Digital, Powder, Design, Selective*)

Resumo

A fim de desenvolver os melhores conceitos e parâmetros para os processos de produção industrial, foi elaborada uma análise dos conceitos de engenharia e design aplicados na esfera dos métodos de fabricação aditiva. Com foco na deposição em cama de pó, este trabalho apresenta resultados de experimentos derivados da deposição digital seletiva de pó, utilizando abordagens para estudo, assistência e otimização dos parâmetros influenciadores no processo e resultados das peças produzidas. Explorando temas como temperatura de sinterização, taxa de aglutinação, processo de densificação entre outras, adicionando estes conceitos em materiais cerâmicos e minerais

Palavras-chave: *(Tecnologias, Aditivo, Digital, Pós, Design, Selectivo)*

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List of symbols and nomenclatures

IPL - Polytechnic Institute of Leiria.
AM - Additive Manufacturing.
DSPD - Digital Selective Powder Deposition.
CDRSP - Center for Rapid and Sustainable Product Development of IPL.
DDM - Direct Digital Manufacturing.
CAD - Computer-Aided Design.
CAM - Computer-Aided Manufacturing.
CNC - Computer Numeric Control.
SM - Subtractive Manufacturing.
FM - Formative Manufacturing.
STL - Stereo-lithography.
FDM - Fused-deposition Modelling.
SLS - Selective Laser Sintering.
SLM - Selective Laser Melting.
LOM - Laminated Object Manufacturing.
SGC - Solid Ground Curing.
DSPC - Direct Shell Production Casting.
3DP - Three-dimensional Printing.
RP - Rapid Prototyping.
ASTM - American Society for Testing and Materials.
SL - Stereo-lithography.
SLA - Stereo-lithography Apparatus.
FFF - Fused-filament-fabrication.
PLA - Polylactic Acid.
ABS - Acrylonitrile Butadiene Styrene.
UV - Ultra-violet radiation.
MMAM - Multiple Material Additive Manufacturing.
DPP - Dry Powder Printing.
 μm - Micrometer.
Pa - Pascal.
MPa - Mega Pascal.

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Chapter 1

Introduction

From the construction of new concepts for product prototyping, new strategies and technologies are being developed to reach different targets and spaces in the market. Whether in liquid or solid state, extrusion or in powders, additive manufacturing methods have highlighted good results in the development of prototypes with unique aspects and for specific situations that reach different areas in different branches such as aeronautics, medicine, industry, transportation, among others, aiming to improve the development of materials, increase performance, reduce waste and increase quality of the final product.

Seeking to contribute to the development of these new techniques, this exploratory project represented by the Polytechnic Institute of Leiria (IPL), analysis and concepts standard related to the applications of ceramic materials and other materials such as basalt and glass in additive manufacturing processes (AM).

Adopting the powder bed method and using a digital selective powder deposition system (DSPD), this study consists of adopting parameters related to the behavior of the selected materials. Heading to the Center for Rapid and Sustainable Product Development of IPL (CDRSP) in Marinha Grande - Portugal, there is an DSPD machine Iro3D. Developed by Sergey Singov, this machine uses the concept of DSPD on powder bed to print metal parts and then take them to the oven to be cooked and where a composition process can even occur. Having four distinct compartments for main materials and supports, connected to also four nozzles, which deposit the materials according to the codes defined by the slicer software, a machine showed great promising potential in the sphere of parts development purely or with metallic compounds.

In order to improve performance and establish parameters for other materials that can be explored in this process, we have adopted the objective of analyzing the results obtained through the study of ceramic materials, such as faience, stoneware, porcelain and glass. Considering evaluation criteria such as granulation of the powder, direction and position of the support material, pre-preparation for cooking, agglutination and resistance, several samples were collected and evaluated by tension tests and morphology analysis.

1.1 Thesis Motivation and Objectives

In the industrial production sphere, focusing on direct additive manufacturing processes, automated production processes whether mechanical, chemical, tangible or virtual, all of these process technologies are derived from the context of machining development and optimization, study of materials performance and automation of industrial systems, in order to obtain better results in the final product or some reduction in the process, be it in time, resources, energy, labor, maintenance, etc.

In this dissertation, a relation will be presented between the design and engineering processes in direct digital manufacturing (DDM) and AM in industrial parts using systems of powder bed AM based on digital selective powder deposition, defining this research based on four proposals: analysis of sintering, melting and degradation temperatures; agglutination and powder binding process; DSPD systems and densification process. Thus, demonstrate the results of experiments carried out with several different types of powder including basalt, ceramic and glass.

1.2 Thesis organization

In order to achieve a better understanding of the development of the work, is structurally divided into eight chapters. Concluding this one, the next topics will be presented according to the following list:

- Chapter 2: In the beginning, it is introduced a general review and presentation of the methods and technologies that will be studied in this work.
- Chapter 3: It is presented and defined the State of Art of the technologies, showing the latest ideas and methods of the interaction regarding powder bed and AM, economic and business models, sustainability issues and materials properties.
- Chapter 4: This chapter presents the scope of this work. The four research hypotheses proposed previously are described, grounded and their processes and methods analyzed.
- Chapter 5: Experimental research phase. Where the selected materials, processes, design software, study case and methods are listed.
- Chapter 6: The results of the analysis processes and synthesis of the materials and methods used for future oriented design are presented in this chapter.
- Chapter 7: This chapter presents the conclusion of the studies derived from AM processes involving powder bed methods based on DSPD, and design digital systems.

- Chapter 8: Future expansionary potential and references.

Chapter 2

Design and Engineering integration in the Industrial Manufacturing

2.1 Introduction

While the technology improves the human being way of life, also provides a improvement in the manufacturing processes and techniques in the industrial environment. A good relation between the design and engineering concepts is crucial to achieve the best efficiency in the production processes not only in techniques and methods of creation but also in availability. This chapter introduces how this relationship can innovate the means of production, breaking parameters related to forms, processes and materials.

2.2 Design and Engineering Analysis

Engineering is the study and application of the various branches of technology, with the function of materializing and making an idea into reality. It is dedicated to the design, improvement and implementation of systems that involve people, materials, information, equipment, energy and greater knowledge and skills within a line of scientific and mathematical knowledge. Engineering seeks to solve problems and satisfy human needs [1], it also involves the application of inventiveness and ingenuity to develop a certain activity. Among the various tasks of the engineer, we can highlight the research (in search of new techniques), design, development, production, construction and operation.

The designer aims to develop and design parts and products, valuing their functionality, aesthetics and social impact. This professional elaborates the visual identity of manufactured or industrialized products considering parameters such as material adequacy, ergonomics, environmental attention, practicality and beauty to the product, also responsible for the selection of the raw material used, the definition of the production process, the monitoring of

the manufacturing processes and commercialization. Thus, the designer tends to follow concepts such as "useful, usable, desirable, productive, profitable and exclusive" that manifest themselves in common between industrial sectors and types of product, both for the company and for the consumer and is related to the area of knowledge, projecting the characteristics of the products that can be condensed into the macro-dimension interface performance [2].

"Industrial design must be permanently integrated with engineering, so that the products designed have not only a good technical performance but a good performance at the interface level." **Liliana Rita Leiria Rosa, 2013**

In this context, the union of the concepts of both professions, provides the emergence of new means of production and improvement of the final results, respecting the parameters and limitations of each area in all stages of the production process [3]. Thus, the term "product engineering" is generated, adding scientific principles and technical information to those of creativity and imagination [2]. This new concept of design can be applied in all ramifications of the technological and production sectors. Figure 2.1 shows a example of one of these applications.

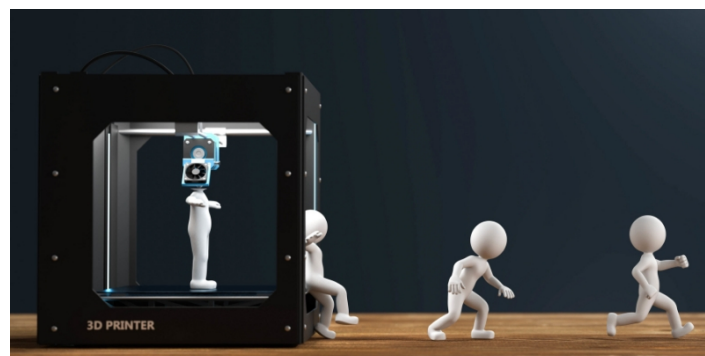


Figure 2.1: 3D printer becomes ideas into reality [4]

"Design is not just what it looks like and feels like. Design is how it works". **Steve Jobs, 2003.**

2.3 Prototyping and Automated Processes

Prototype is defined as a first and original concept of what was or will be developed. It is considered a preliminary stage of the product before its official launch on the market. An important and vital part of the product development process, where the model can be tested by performing its functions applied in the environment for which it was manufactured, generating performance information for future optimizations. The aim of the prototypes phase

is to provide evaluation of the design problems and develop posterior improvements [5], acting as an operating version of a solution.

The AM processes is one of the means of automatic manufacture, which allows to obtain parts and models from designs and digital information [6]. With the evolution of computers, advances happened in many computer-related areas, standing out Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and Computer Numeric Control (CNC). These control system technologies are what allowed the emergence of manufacturing processes.

These processes can be classified as 3 different types of systems:

- Liquid-based systems: The material start in the liquid state, being transform in a solid state by a process known as curing.
- Solid-Based systems: Range all the materials in the solid state. Including wire, roll, laminates and so on.
- Powder-Based systems: This is classified as a different category of the solid state, using powder in grain-like form.

Regarding the automated fabrication processes, Figure 2.2 shows that it is possible to separate in 3 different fundamental groups: additive manufacturing, subtractive manufacturing (SM) and formative manufacturing (FM).

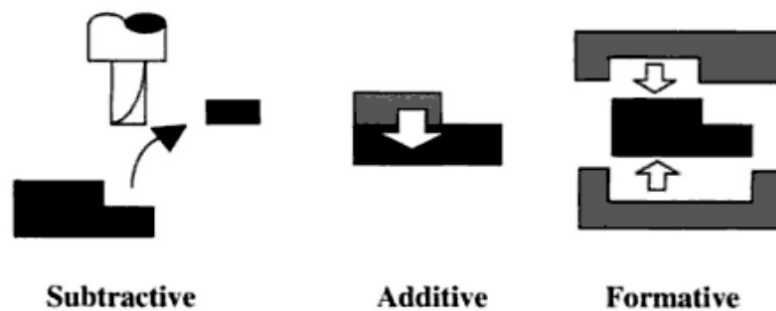


Figure 2.2: Automated Processes - AM, SM e FM [7]

This three categories presents different ways of working with the material and produce parts:

- Subtractive Process: This process starts from the premise of initially having a block of the chosen material with dimensions larger than the final piece, where the material is removed and sculpted until it acquires the desired shape. It constitutes most of the machining processes, using CNC and others. Figure 2.3 illustrate one of this applications that can cover several areas such as grinding, milling, drilling, turning, among others [8].



Figure 2.3: CNC: Automated Machining Process [9]

- Additive Process: This process is the most relevant in question. Unlike the subtraction process where the material is removed, AM consists of the application of the material, being introduced layer-by-layer until it acquires its final shape [6]. This process consists mostly of the CAD format. Using stereo-lithography (STL) concepts, the digital model is divided in several triangles. This "slicing" of the part is used by the machine as reference to input the material. The process can be divided in many variations such as fused-deposition modeling (FDM), selective laser sintering (SLS), selective laser melting (SLM), among others which will be described below. Figure 2.4 shows the additive layer-by-layer process of rapid prototyping. Another examples of AM processes include laminated object manufacturing (LOM), solid ground curing (SGC), direct shell production casting (DSPC), and 3D printing (3DP).



Figure 2.4: The concept of AM in the houses construction [10]

- Formative Process: This process is closer to conventional manufacturing processes, where mechanical forces are applied to the material to reach its final shape. One of this processes is injection molding describe in Figure 2.5, however, several others are included in this fabrication process such as bending, forging, electromagnetic forming and so on.
- 4. Hybrid Processes: Is possible to combine two or three different processes to gather the best advantages of each other. It is has a significantly expectation about how this hybrid processes can have a big impact in the production of the industrial parts in the

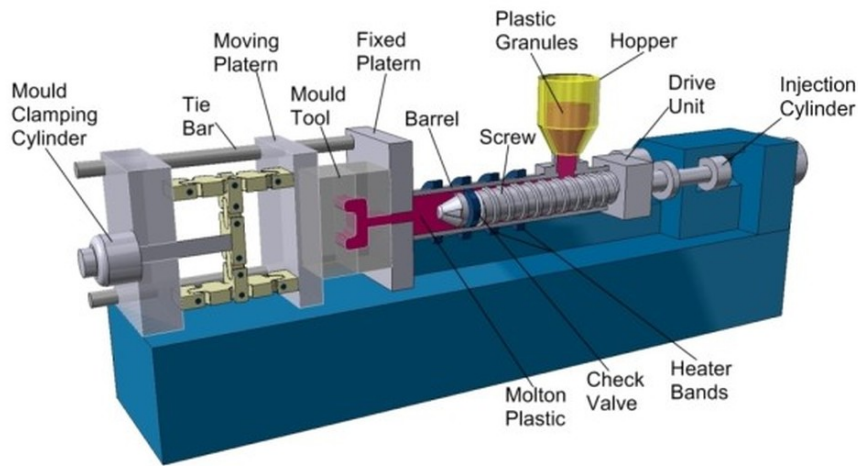


Figure 2.5: Plastic Injection Molding [11]

future. An example of hybrid machines is progressive press working that combines subtractive (as in blanking or punching) and formative (as in bending and forming). Thus, two or more fabrication processes interacting to produce a better result [8].

2.4 Technologies of the Manufacturing Processes

From the technological processes that appears in this new stage, AM stands out. Coming from the concepts of rapid prototyping (RP), old term to refer to the production of parts for analysis and testing before the production of the final product. Nowadays, the manufacturing process has been developing using automated manufacturing processes based on digital information. The sphere of applications using AM, has been rising every year, be it in the industrial or academic fields, or even domestic uses. Nowadays, it represents great technological relevance in several industrial sectors, such biomedical, automotive and aerospace [12], bringing advantages like mass optimization, produce complex parts, fast prototyping, saving waste and free design [13].

According to the American Society for Testing and Materials (ASTM), in the paper ASTM terminology (designation: F2792.12a) AM is described as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [14][15].

The norm categorized AM in several process, as shown on Table 2.1. For the propose of this project, the relevant categories is Material Jetting, Binder Jetting and Powder Bed Fusion, considering the original functionality of Iro3D and the established targets.

A general review about AM and the most common and accessible types of production

Table 2.1: ASTM-STANDARD F2792 - [14]

Process	Principle
Binder jetting	A liquid bonding agent is selectively deposited to join powder materials.
Directed energy deposition	Focused thermal energy to fuse materials by melting as they are being deposited (Laser Cladding).
Material extrusion	Material is selectively distributed through a nozzle or orifice (Fused Deposition of Metals, FDMet).
Material jetting	Droplets of build material are selectively deposited.
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed (Selective Laser Melting, SLM).
Sheet lamination	Sheets of material are bonded to form an object.
Vat photopolymerization	Liquid photopolymer in a vat is selectively by light-activated polymerization.

parts in the market to the users concerning AM processes is presented. Fused deposition Modelling (FDM) and Stereo-lithography (SL) are developed as two examples of these AM technologies to give a general understanding about the concept of layer-by-layer production and stereolithography CAD files (STL), providing a in-depth view about the context of this work.

2.4.1 Fused Deposition Modelling (FDM)

The FDM or fused-filament-fabrication (FFF) process is currently the most accessible for popular consumption. It was developed by S. Scott Crump in in the late of 1980s and have as market leader the Stratasys. It is a solid-based system, where a long filament is extruded from a nozzle-shaped workhead and deposited on the production table layer by layer. The motor pushes the filament through a tube towards the heated nozzle, this material is melted and when applied on the heated table or on the other layers it has a cooling rate of 0.1s, causing the layer to merge with the previous one . It is possible to change several parameters for production, including temperature, speed, cooling, height of layers, etc. The lower the height of the layer, the higher the quality of the piece. Industrial printers usually have greater accuracy than desktops. It focuses on thermoplastics, wax and other polymers, the most popular being Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Nylon, among others.

Transforming a 3D digital model into an STL file format, you can slice the piece into small triangles. In this way, the system can read the settings from the file and use them as a basis for production. Through one or more extruders, is possible to observe in Figure 2.6 a thin filament of the chosen material is extruded and injected on the deposition table (work area) in the areas defined by the slicer software. Thus, the process is repeated in the new layer above the previous one, until reaching the final shape of the desired piece. To ensure that the

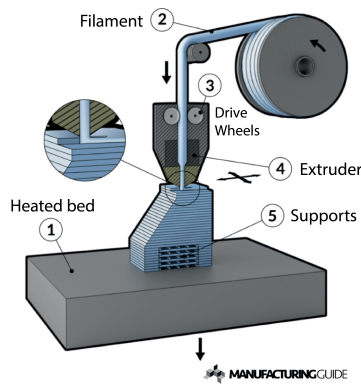


Figure 2.6: FDM Process [16]

piece is fixed on the table, supports are created to support the piece. Being built differently from the part itself, the support structures, even those that are dissolved in water solution are easily removable and breakable. These supports can be automatically generated by slicing software or designed specifically by the user.

Axes X and Y are used to move the workhead to deposit the material and create the layer, after that uses the Z ax to move up and adjust to the position of the new layer, thus building the part from the bottom to the top.

2.4.2 Stereo-lithography (SL)

Develop by Chuck Hull in the middle of the 1980s and patented in 1986. Currently, is manufactured specially by 3D Systems and Sony, the market leaders of the stereo-lithography apparatus (SLA) machines. This process is derived from liquid-based systems. Usually used with thermoplastics (elastomers), being resin the most typical material. A platform is immersed in a tank with a liquid batch of photo-reactive resin and polymerized by a UV laser beam, aided by galvanometers mirrors. The laser cures a fine laminated layer and then the platform moves in the Z axe to go down and repeat the process until the final result is achieved.



Figure 2.7: SLA Machine: Printing parts from resin [17]

SLA presents the best performance regarding resolution and smoothness, especially in small parts [18]. Figure 2.7 shows how it is used to produce presentation models with very detailed parts.

Chapter 3

State of Art

In this chapter, is established the State of Art of the previous technologies applied in the industrial manufacturing. Next, directing to the aim of this project, is presented a review about powder bed deposition technology in AM. Several categories differs the strategies to work with powder grains of materials, like metals, thermoplastics, and ceramics. Through both standard and selective deposition, through lasers to binders subtracts, the diversification and advantages of this process will be explored during this chapter.

3.1 Powder Bed Technology

Powder bed technologies is a set of technologies that use the AM layer-by-layer concept through the use of powder beds to produce pieces of shapes and derived materials.

Using equipment that contains a powder bed that moves vertically according to the height of the specified layers, different technologies present different approaches to build the parts through melting, composition with binders and additives or even sintering process.

Among these technologies, the most common processes are SLS and SLM, which were considered important to stand out for a better understanding of the DSPD technology addressed in this project.

3.1.1 Selective Laser Sintering (SLS)

The SLS process is derived from powder-based methods. Develop by Deckard and Bourell in the Texas University in the end of 1980s.

Using powder as base material, a fine layer of the powder is deposited in the platform. A focused laser beam is used to sinter the powder particles and create the 2D shape in

the selected locations of the layer, according with the parameters of the STL files. Then, the platform moves in the Z axis and a new layer of powder is applied and the process is repeated, as shown on Figure 3.1. In that way, the powder is transformed in a solid by the sintering, building the 3D part geometry. In addition of that, aiming avoid and prevent deformations, is necessary to maintain a constant and uniform temperature [19].

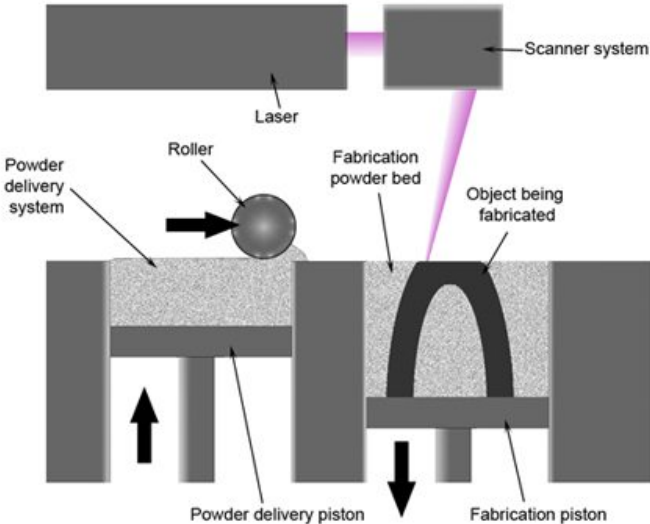


Figure 3.1: SLS PROCESS [20].

At the end of the process, the part is removed from a solid block of powder and cleaning. As produced in a block, there is no need for supports materials in the production. The waste of the powder that was removed and not sintered can be recycled to produce new parts.

As all the processes of AM, SLS can generate parts without restrictions of geometric complexity, Figure 3.2 shows the possibility to build parts that could not be produced by conventional machining. Moreover, support a wide range of processing materials, such as thermoplastics, ceramics and metals.

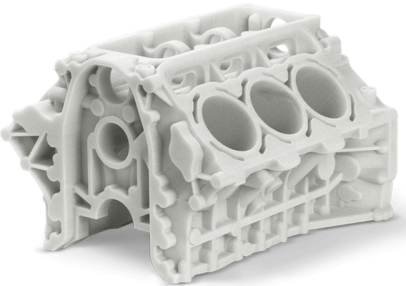


Figure 3.2: Part built by SLS process [21]

3.1.2 Selective Laser Melting (SLM)

This process has the same principles of the SLS methods. Both SLS and SLM are processes derived from the powder bed deposition methods. Focusing in metals, this type of production can generate parts with the most complexity shapes in copper, aluminium, nickel, stainless steel, among others.

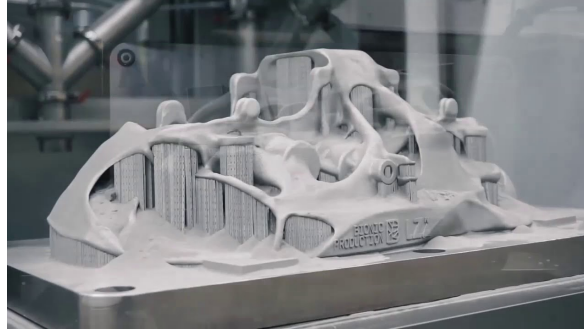


Figure 3.3: SLM 3D PRINTING [22]

The metallic parts generated by this process can be used for several applications such as medicine, jewelry and other design projects. Figure 3.3 represents a final part built by SLM process.

3.2 Selective Powder Deposition (SPD)

Finally, using the parameters of powder bed deposition processes, the SPD acts in a different way, introducing the opportunity to work with several material in the same time. One of the pioneers of this new technology is Iron3D and AeroSint. Supporting different types of powder, the deposition is applied in a specific work-area, being sintered by the same structure in format of nozzle. Using a based metal to infill the component and a metallic powder to surround the part.

"The ability to print multiple materials from an additive manufacturing system can improve either the mechanical properties of the parts or provide additional functions to the 3D printed parts" S. Chianrabutra, 2017.

3.2.1 Aerosint Technology

Aerosint is a SPD process that approach a different strategy of the first ones. In this case, there are no nozzles, but a drum that passes over the built area depositing the powder material. As many drum coupled, more materials is possible to work, achieving the multi-material

function. The machine works with a SLS system integrated, and is based on line-by-line method as shown in Figure 3.4. Can reach 200mm/s rate, being faster than any other SPD technologies based on pipettes.

The project aim to be less sensible to the powder characteristics than others pipette-based methods, reducing the limitation of different parameters like flow rates for each material [23]. The idea is the process be most independent of the material as possible, allowing be applied easily in others groups of materials with "less-than-optimal" powder size distribution and flowing characteristics such as ceramics, metals and polymers.

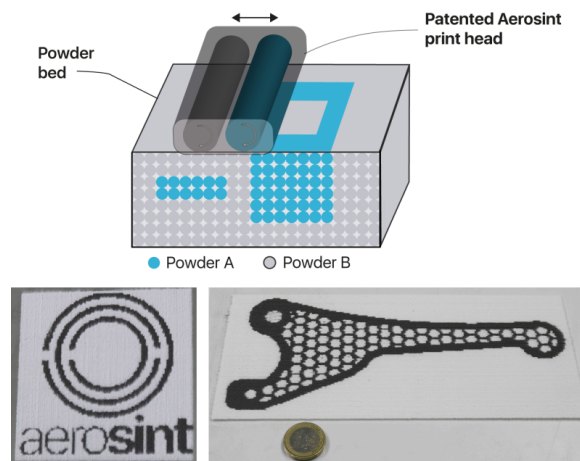


Figure 3.4: AEROSINT Method [23]

Beyond all the benefits derived from multi-powder deposition through reduction of powder waste residues, reduce post-processing time and material cost save, this technique can be applied to production of products and parts designated to several industrial sectors, such as; no waste printing of exotic polymeric materials with high performance for medical application, aerospace and automobile; Multi-polymer and multi-metal printing, combining the material properties in order to achieve the best performance; co-printer metal-ceramic, combining heat resistance and hardness of ceramics with the elasticity and strength of metals; and so on.

3.2.2 Dry Powder Printing for Multiple Material Additive Manufacturing (MMAM)

In order to obtain best results in AM and improve the parameters of the manufacturing processes, new technologies has growing up in the last years. As the usual AM processes works with a single material, the idea of operating with multiple material at the same time was investigate along the years. Then the MMAM system was created and presented as new technology to three dimensional multiple material parts.

Develop by Evans, in 1990s and commercialized by the Objet company, the original MMAM concept uses a direct inkjet printing to produce the parts, however, it was limited

only to print photo-polymers materials, presenting a inferior mechanical properties and functionalities comparing to the metallic and ceramic processes.

In Dry Powder Printing (DPP), an ultrasonic device holding a piezoelectric transducer is used to improve the performance of the deposition rate. A glass nozzle used as a funnel and computer control systems is what integrates the vibration-assistance. Powder drops are discharged directly from the dispenser; the discharge breaks the dome structure formed in the orifice, which activates a voltage signal pulse to the piezoelectric transducer attached to the dispenser [24].

According with Chianrabutra (2017) studies, the high resolution depends on the nozzle orifice geometry, standoff distance and moving speed, flow rate and the signal voltage used to activate the piezoelectric transducer.

3.2.3 Iro3D Technology

This printer represent the scope of this work. Using this machine for explore the properties of DSPD, is possible to uses any type of powder that can fluid from the nozzle, allowing to work with hard metals such as lead, tungsten, cobalt, iron and others. Can combine all types of metals where the fusion point of the fill metal be lower than the surrounded powder. In Figure 3.5 is possible to notice the different recipients to storage the powders. In this case, the metal powder is not sintered but infused by the fill metal, preserving the shape and avoid shrinkage. The printing time can variate depending of and size, but have a average time of 24h for a single part. The applications of this DSPD process can range from moulds components for plastic injection molding, motors for rockets and automobiles, up to safe box doors.



Figure 3.5: Iro3D Machine [25]

Post-processing

After the part is printed, it is necessary to submit to a post-processing in an oven to bake it. The cooking temperature must be between the fusion point of the deposited fill metal and the metal powder. For instance, if choose copper as the fill metal and iron powder, the temperature must be between the fusion point of the both materials [25]. Considering the fusion point of copper as 1084°C and the iron as 1538°C, the temperature of the oven must be around 1184°C.

If the powder belongs to reactive metals, it is necessary to be coated by another metal or carbonate. When the reactive metals are in the fill, a vacuum oven with nitrogen or argon can be used.

Powder Characteristics

In order to guarantee the good flow rate, the size of the powder grains or particles must be at least 10 times smaller than the nozzle hole. However, grains smaller than 40µm are not recommended, due to the fact of tending to toughen up and presenting a health issue, once that the particles are more susceptible to propagate in the air. Either the powder and the fill metal can not have much impurities in order to avoid porosity, oxidation and others issues that can interfere in the final result.

Powder as copper and zinc its commercialized by specific websites such as "makin-metals.com" and "RotoMetals". Other material such as stainless steel, iron, Coke Carbon and supported material in "tridprinting.com/Iro3d"

All the technical information was extracted from Iro3D official website.

3.3 Materials

Considering the current demands for resources already exploited by the industry in the production of materials for products and machines, the use of materials that are easy to explore and refine was chosen as a challenge for this project. The best-known ceramics such as faience, stoneware and porcelain will be used and analyzed with the intention of adapting them to the DSPD process.

These materials are of great relevance when dealing with the theme of sustainability, since they are abundant materials and still allow their use through materials and powders derived from other products and leftovers, such as civil construction, for example, recycling

and reuse these material powders for new industrial purposes.

The material applied in SPD will be usually derived from powder of metals, ceramics, glass, support and part powders, however, minerals like Basalt and Granit can also be sinterize and tested in the production field [26].

The use of the basalt in question fits with the idea of presenting the use of a little explored material in this branch of AM. Its industrial exploration is mainly in masonry areas, aggregates of civil construction and as ornamental stones for sidewalks. However, its mechanical characteristics have great potential for applications directed to engineering and development of parts with good performances, in places with limited resources.

Basalt is basically the cold magma released by the earth's crust, coming from the deepest layer of the mantle. It has great resistance and hardness, besides being light, it has good thermal conductivity, geotechnical characteristics and resistance to weathering. Basalt fiber, for example, composed of basaltic rock and minerals such as plagioclase, pyroxine and olivine, have, in addition to the characteristics mentioned above, also resistance to heat and vibrations, being superior to other fibers in physical-mechanical properties.

3.3.1 Sustainability Relevance

Nowadays, the impact of the production and exploration processes of materials is a growing concern to ensure the support of available resources on the planet for the next generations to come. In addition, the importance of reducing this impact on the environment is something that must be considered in each project developed for industrial, commercial and personal areas. For this, several strategies such as creating new materials, reducing waste, generating new energy sources, design parts considering circular economy, among others, are being considered in the sphere of development of processes, machines and materials, relating production to the sustainable development of products and applications.

In order to attribute these values to the project developed by this work, some characteristics were established, contributing to reduce the impact caused by the manufacturing field.

Considering the materials normally used, this work focuses its studies on materials of great abundance on the planet, such as ceramics, basalt and glass.

Another strategy adopted for the project's sustainability was the use of powdered silica sand as a support material. This powder has a sintering temperature higher than the main materials used. In this way, during the sintering and baking process of the parts in the oven, the silica remains stable and does not reach the crystallization state, making its shape remain

in the powder state, while the materials used for the parts, whether ceramic, glass or basalt, crystallize and sinter. Thus, it is possible to reuse the silica powders again when repeating the process to produce new parts.

Chapter 4

Expansion of the Limits of Manufacturing and Design - Powder Bed Additive

4.1 Hypotheses

This section demonstrates the planning and hypotheses to be explored and analyzed using the established parameters. Granulation size, deposition system, temperature and agglutination and bonding process is the parameters that have been evaluated.

4.1.1 Powder Granulation Size

Its propose to be test different types of granulation. For this study, its selected 3 different sizes to observe the difference in the results.

- Powder granulation of 200 up to 299 μm
- Powder granulation of 100 up to 199 μm
- Powder granulation of 63 up to 99 μm

4.1.2 Selective powder deposition systems

Explore differences in the flow, deposition and precision of the powder, through two different nozzle sizes.

- Analyze the flow and deposition of different granulation size of powder through a nozzle of 0.9 mm.
- Analyze the flow and deposition of different granulation size of powder through a nozzle of 1.9 mm.

4.1.3 Agglutination / bonding process of powders

This proposal is to explore the difference in agglutination strategies of the selected materials after printing. The study discusses three ways to analyze the agglutination of materials and verify the results of compaction, solidification and morphology.

- Simple printing prepared to cook.
- Application of compacting pressure with or without small quantities of water to stimulate and reinforce the agglutination on ceramics materials and analyze its morphology.

4.1.4 Materials: Analyze sintering and melting and degradation temperatures

In this approach, the objective is to verify the morphological relationships using variations in the cooking temperatures suitable for each of the materials used, aiming to achieve differences in the results in matters of structure, compaction, chemical reaction and resistance in the post processing.

Chapter 5

Experimental Analysis

To expand the limits of performance in DSPD process, aiming to reach new conditions of production, materials and results, the proposal of this work is to adapt the mechanisms and utilization of Iro3D from metal process to ceramics. The selected materials was exposed to several steps of analysis and tests. Part of the project was to verify the viability of the materials proposed, as basalt, glass and faience in the DSPD process utilizing the system of Iro3D, in addition to evaluating how materials behave during selective deposition processes, was also evaluated the materials sintering ability.

5.1 Sintering Synthesis

Sintering is basically the process of removing pores, stimulating a strong bonding of the particles, causing a retraction of the material submitted to certain pressures and temperatures. The main parameter to achieve this process is the reduction of the surface area and the surface energy applied to the particles, replacing the loose powders with high energy rate surfaces, with solids connected by the grain contour having low associated energy [27].

In the scope of application to the ceramic materials used, this process can be separated into categories that define the sintering performance in the materials, being used to ensure a better efficiency to achieve the desired result.

The initial sintering process presents a light connection between the particles at their points of contact, maintaining the grain sizes considerably and creating a reduction in material density of approximately 10%.

From the introduction of more energy, the process reaches intermediate sintering, creating greater connections at the contact points and increasing the grain sizes. As a result, the porosity of the material has decreased and the grain contour has increased, making it possible for the part density to decrease by up to 90% at its final stage.

In final stage of sintering, the grains get even bigger and the pores close slowly, further reducing the density of the part.

5.2 Selected Materials

As explained previously, the focus of this project is on ceramic materials and minerals. This kind of materials has a abundance quantity and spared for the whole planet.

To prove its great capacity for exploration and use, this materials represent a target to the future, being able to provide new products and techniques even in regular ways of production as in the high-end of human technological methods of production, reaching places that is necessary to explore new kinds of resources.

5.2.1 Main Materials

In the topics below, is presented a quick contextualization about the main materials used, such as porcelain, stoneware, faience, glass and basalt respectively.

Porcelain

The origin of the word porcelain comes from the Italian term *porcellani*. Porcelain was produced in China in the Tang Dynasty and made from the cooking process of two minerals (feldspar and kaolin). Porcelain is a white waterproof and translucent product, which can be worked in liquid, paste and powder states. It has the characteristics of glazing, transparency, resistance to corrosion, totally free of pores and sound, so it is different from other ceramic products (such as earthenware, stoneware and crockery). This translucent feature comes from the fact that it is the only one to be glazed and cooked at temperatures of 1.400°C, in a reducing environment [28]. The raw materials of porcelain are basically: clay, quartz, kaolin and feldspar. Porcelain has high mechanical resistance, low porosity and high density, in addition to durability, safety, soft touch and beauty.

Faience

Like other types of ceramics, faience is a low-calorie porous paste that can be waterproofed after being glazed. It has a light gray tone that is clear after cooking. It is a paste that exists a lot in the soil, therefore, compared to porcelain, the particularity or nobility of faience is less

and, compared to stoneware, its "utilitarianism" [29] is also weaker, as this ceramic is lighter and has more porosity. The main difference is the large number of decorations, colors and finishes that can be explored.

Vivid colors, matte/glossy finishes, metal and iridescent chandeliers, make it infinitely possible to transform this "bad paste" into everything you want, including value-added items. There is no doubt that when the objective is aesthetics, it is the preferred paste, therefore, when decorative ceramics are needed, it is the most suitable material because, by definition, they are objects of visual attraction.

Stoneware

Like porcelain, stoneware is also a high temperature ceramic, but unlike the first type, it is a natural plastic paste with a hard, dense and waterproof composition, with a pale yellow/grayish tone. They can achieve very organic results, and the mineral properties of this paste can be emphasized in terms of color and texture. Although the melting property due to the high temperature during the cooking process allows very specific reactions, traditionally, the possible range of decoration is smaller than that of the low-fire glassware used to make faience.

This set of characteristics makes stoneware the ideal solution for dishes, since the low porosity of the paste after cooking guarantees high resistance, making it a viable solution to effectively respond to the daily washing needs of table ceramics [28].

In turn, the aesthetic characteristics also explain why this paste is so popular, even for decorative purposes, it brings together all the properties to give it an organic and natural look, being increasingly sought after around the world.

Glass

It's not well defined how where and when the glass was discovered. Some legends from Roman sailors tell us stories about the Phoenicians making glass by accident, while they were making their meals in a beach sand. Glass is a fairly common material made from silica (SiO_2) and specific oxides such as Na_2O , CaO , MgO , among others. Unlike materials with periodic three-dimensional structure, such as metals for instance, glasses have a random three-dimensional structure, being defined as glassy or amorphous solids. To obtain these solids, a liquid material is cooled fast enough to avoid the crystallization process. These solids have a high viscosity rate (compared to water, the glass has a value of 10^{18} Pa x s against 1 Pa x s of water) [30]. Nowadays, different kinds of glasses are used around the world for manufacture engineering, aesthetics, among others, having melting points varying

from 900°C to 1600°C.

Basalt

Basalt comes from volcanic rock. It is derived from basic magma, fluid magma. They appear because they are not as dense as the rocks in the earth's crust. In this process, the magma reaches the surface and produces basalt. In other words, basalt is the general term for solidified volcanic lava. The chemical composition of basalt is very constant, containing SiO₂ (silicon dioxide) ranging from 43% to 52%. It has a high content of calcium, iron and magnesium but we can also find cobalt and chromium. The most common variations of this material are: tholeitic basalt, alkaline basalt, calc-alkaline basalt. It has some physical properties, such as dark color, fine texture and a small amount of vitreous material, in addition to very hard properties. Its melting point is 1350°C, so it is considered to be fireproof.

The molten basalt reaches a hardness value of 8 on the Mohs hardness scale. For comparison, only diamonds can reach the highest value of 10. Because of these characteristics, molten basalt can provide excellent wear protection. However, it is sensitive to impact and therefore cannot be subjected to thermal shock. Basalt is one of the most abundant rocks on Earth. Powder, wool and fibers can be obtained from basalt. The fiber comes from a foundry and has mechanical properties such as rigidity, strength and lightness, immunity to nuclear radiation, ultraviolet rays, biological and fungal contamination, in addition to excellent chemical resistance and high temperature, and low correlation of sound absorption and thermal conductivity.

5.2.2 Materials of Support

To produce the materials by the process of DSPD, it is necessary to input a material as support. Considering the objective of this project, the material chosen was silica, as already used to produce parts by sand casting molding and others techniques of manufacturing.

Silica Sand

Silica sands have as main components in its composition the SiO₂. Being apply in several applications, such as manufacturing of quartz glass, fiber optics, silica film, metallurgical fluxes, among others, through high purity quartz sand, that is the main material for these processes [31]. Is one of the silicate minerals that have in your properties, the high hardness rate, anti-friction and low reactivity. Contains 8-10% of water, amount that needs to be decrease for instance, until less than 1% to produce glass materials. It is commonly used

in the foundry industry to manufacture ceramic parts and metal casting in a form of rounded grains, washed and graded to 100–120 μm [32], having a sintering point around 1200°C.

5.3 Processes, Analysis of Processing Steps

In this section, the methodology used and the steps taken from the separation of materials to the final piece will be presented. The process is divided into seven stages, grinding, sieving, construction of the crucible, deposition of the material, preparation for cooking and finally, the cooking itself. All steps are of equal importance for a good performance in the process, to adhere more accurately, several machines were used to assist in production, all provided by CDRSP.

The materials that showed too much moisture in their composition, demonstrated performance problems in all stages of the process. To solve the problem, they were incubated in a greenhouse at a temperature of 60°C for a minimum period of two days.

5.3.1 Grinding

Aiming to reach the established grain sizes, the bigger grains of each raw material was milled using the MGS SRL 1800-2. The machine shown in Figure 5.1 works with two ceramic vases, that contains inside small ceramic spheres. When the process is on, the vases fixed in iron bars starts to split surround a central axle, that centrifugal force make the spheres inside crash each other with the powder grains. Several times can be necessary regarding the material parameters and amount. The times and cycles can variate according with the strength and hardness of each material. Faience and stone powder showed less resistance and easy to crush. In case of Basalt and silica, presents more resistance, taking longer times of crunch cycles until the reach the expected grains sizes. In first case, it was necessary 7-10 minutes containing 20 ceramic spheres to grind 300g until become smaller enough to go to sift.

5.3.2 Sieving

After the grinding phase, sieving comes. Using a MGS SRL SHAKER-07 shown in Figure 5.2, the three different sizes of sieves were added, concerning the hypotheses proposed. Above all, a fourth was deposited, of 300 μm , to guarantee the maximum size of the powders, followed down by the 200 μm , 100 μm and 63 μm sieves, allowing the desired grain sizes be achieved. With this fourth sieve, the remaining powders can be returned to the grinder, and repeat the process until they are at the ideal size. The same applies if the powder is still



Figure 5.1: MGS SRL 1800-2. Source: CDRSP-IPLeiria, Portugal.

damp, if so, returning it to the greenhouse will guarantee better performance in the process. Faience and silica showed greater need to remain in the greenhouse.

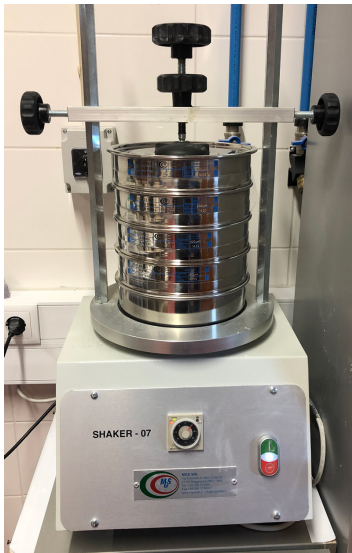


Figure 5.2: MGS SRL SHAKER-07. Source: CDRSP-IPLeiria, Portugal.

5.3.3 Crucible Construction

To fabricate the place where the material is deposited, a draw of a model was designed to be the mold to fabricate the crucible. The design was developed to contain three assembly parts to facilitate the removal of the crucible from the mold. In addition, the design of the based part includes an opening with a resistance bar in the middle to assist in the handling and allows to create the force necessary to remove it from the part. The measures and views are presented in Figures 5.3 and 5.4.

To make the physical crucible, as shown in Figure 5.5, silica, plaster and water was chosen as the materials. For each part, 500ml was producing using a formula containing half

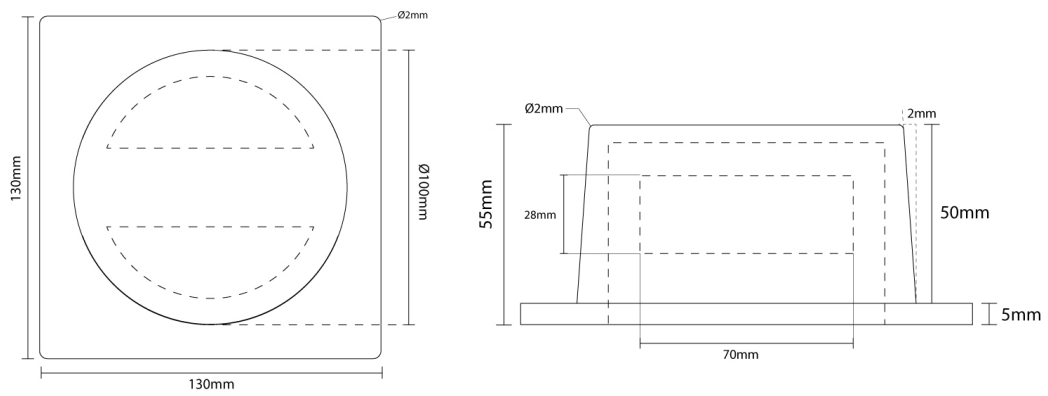


Figure 5.3: Crucible measures - Part 1

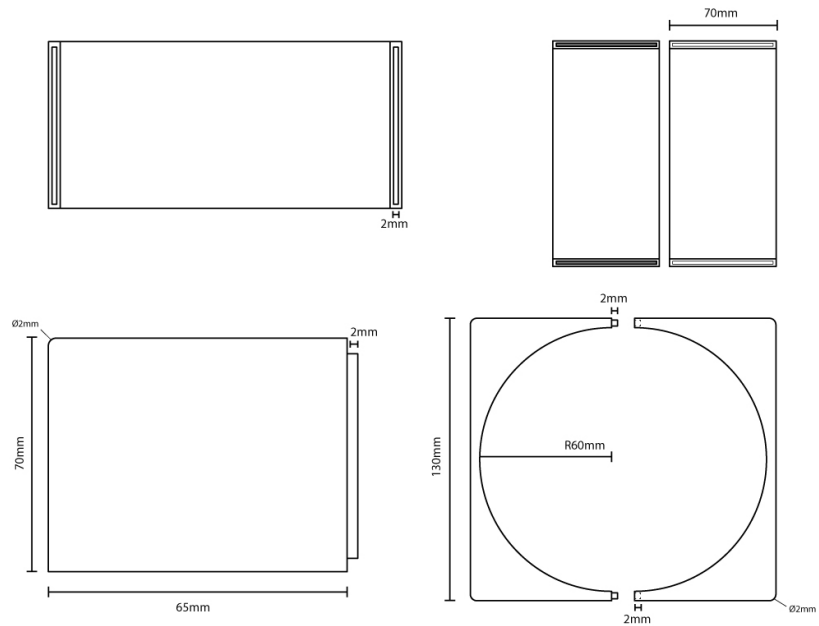


Figure 5.4: Crucible measures - Part 2 and 3



Figure 5.5: Phases of crucible development - Virtual, mold and final

by water, and other half a proportional mix of plaster and silica fumed of 0.2-0.3 μm . After dry and solid, is removed from the mold and goes to greenhouse at the same temperature of 60°C for a period of 6 hours to remove all the moisture.

5.3.4 Deposition of Selected Materials

Iro3D is a machine that uses a DSPD system to print parts using metallic powders as the base material for its system and processes. In this project, the objective is to adapt this process to the materials previously mentioned, as you can see in Figure 5.6, which demonstrates from right to left, the process applied to porcelain, glass and basalt materials. To improve the efficiency flow of the powders, all the materials already processed were placed back in the oven to remove any residual moisture, under the same temperature as the previous steps.



Figure 5.6: Printing samples in porcelain, glass and basalt respectively. Source: CDRSP-IPLeiria, Portugal.

The purpose of this project was to follow the established hypotheses, analyzing the performance in terms of fluidity, compaction, shape and support of the piece, using powders in grain sizes of 63-99 μm , 100-199 μm and 200-299 μm .

The machine contains four compartments for powders in which they are connected to four nozzles for deposition as shown in Figure 5.7. Two of these nozzles, numbered 0 and 2, have a deposition rod with an 8mm radius and with a diameter of the powder release hole of 0.9mm. These nozzles are responsible for depositing the coating material, used as a middle ground for the sintering temperature points between the base material and the support material. The other two nozzles, numbered 1 and 3, with a 6mm radius rod and 1.9mm deposition hole. It will be through these nozzles that the powders of the main materials for parts and support will be deposited, as shown in Figure 5.8.

Deposition was tested in three different ways. Completely closed, as shown in Figure 5.9 on the left and in open mold. The purpose was to analyze the responses of the materials and their thermal properties, depending on the heat exchange with the silica support material and the temperature of the cooking environment. In the same figure on the right, we can see the difference between the deposition strategies.

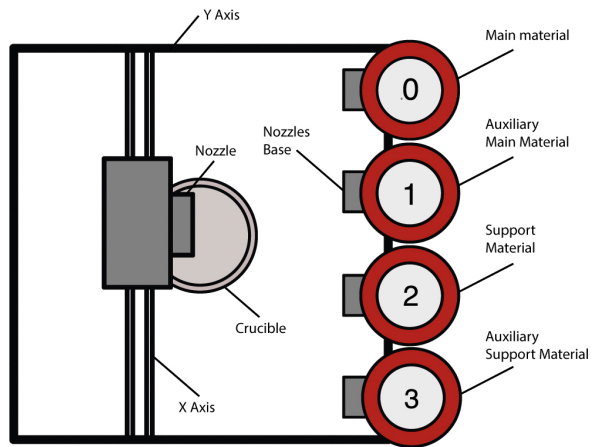


Figure 5.7: Iro3D top view illustration.

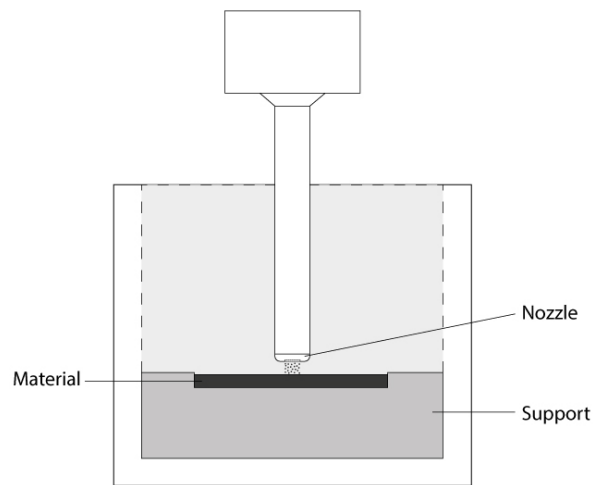


Figure 5.8: Powder application scheme



Figure 5.9: Printing samples with closed molds and open molds respectively

The bottom layer where only the support material resides, in this case silica, remains the same size for all tests, 0.3 mm. This same layer height is deposited at the top, where the mold is sealed, being repeated several times until it forms a thickness of 12 mm. In order to better observe the behavior of the main material subjected to the specified high temperatures, tests were also carried out with the top layer of silica with half the original thickness, containing only 6 mm.

The shapes chosen to be built as samples was a rectangle measuring 70 mm length, 23,5 mm of weight and 5 mm height. This shape standard contributes to the future mechanical properties analysis. The second shape is a standard tensile test specimen 70 mm length, 23 mm weight and 5 mm height. This shape was chosen considering also to study the morphological capability.

Seeking to print the samples with the parameters established for the sizes of the powders. It was at this stage that is founded the greatest difficulties in relation to the performance of the process. These and other analyzes will be developed later in the results chapter.

To apply the powder in the crucible, the slicer software was developed to follow the trajectories below, being the green line the support powder and the red line the main material.

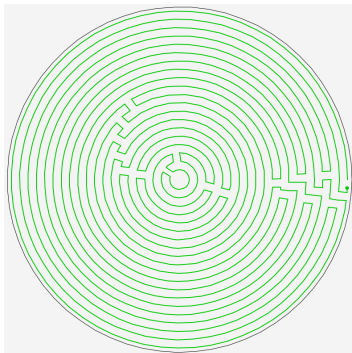


Figure 5.10: First layer trajectory.

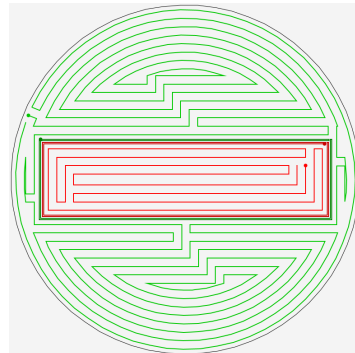


Figure 5.11: Part deposition trajectory

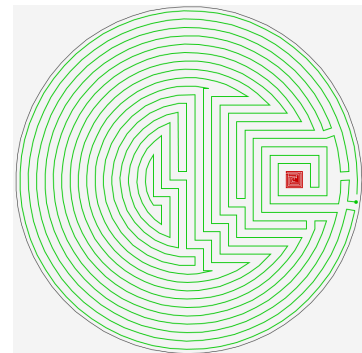


Figure 5.12: Covering and auxiliary tunnel trajectory.

5.3.5 Previous Preparation for Cooking

In this stage, studies related to the agglutination processes will be carried out. These strategies were adopted to reinforce the densification and compacting of particles and grains before going to the oven. For this, three types of strategies were followed to verify their efficiency and results, these were defined according to the standard behavior of these materials during this type of process. Of these pre-cooking processes, which are responsible for strengthening the morphological structure of the final part, we can name them in regular printing, printing with the aid of pressure and printing with the aid of pressure and water.

5.3.6 Cooking

In this phase, each material is subjected to different cooking parameters, varying according to its melting and sintering temperature. Using a oven Termolab MLR 107/04, represented in Figure 5.13 the topics below presented the cycle of the temperature apply for these materials.



Figure 5.13: Oven Termolab MLR 107/04. Source: CDRSP-IPLeia, Portugal.

Materials Parameters

- Basalt

To explore the behaviour of the material during the sintering process, a cycle of temperature variations was established. Figure 5.14 shows the standard temperatures used to Basalt. Running by 4 hours to reach 600°C and being in this temperature for 1 hour to stabilize the silica powder. Then the temperature goes during a period of 5 hours to the value of 1250°C, where the crystallization starts and the sintering process occurs, staying in this temperature for 1 hour until the cycle ends.

For the tests of sintering and cooking, others temperatures were also used to verify how this variation affected the final results, such as 1200°C and 1300°C.

- Glass

To present the study of the temperatures cycle of the glass, the same Figure 5.14 shows the chart to illustrate the temperature and periods used for reach the sintering stage of glass. Running 4 hours to reach 600°C, when the crystallization starts, being in this temperature during 1 hour until rising to 900°C, when the sintering starts. In this case, the temperature stays 45 minutes to avoid the melting of the material. After that, the values decrease to 525°C where it remains for 1 hour to stabilize the glass, then decreasing again for 30 min (0,5h) to finish the cycle.

- Ceramics

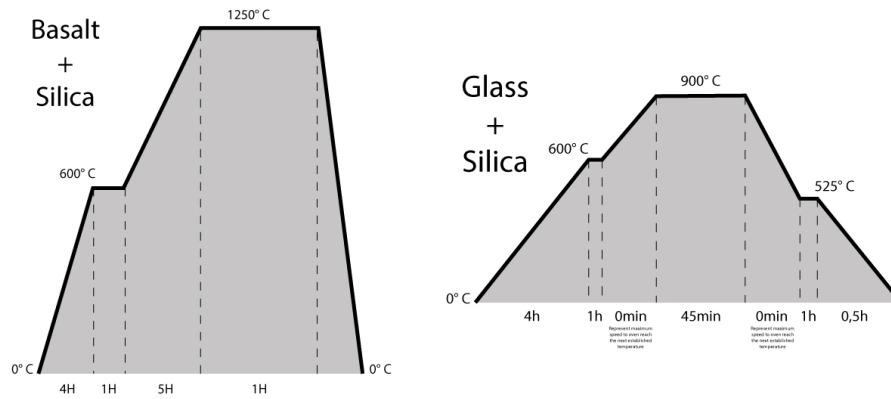


Figure 5.14: Curve temperature of oven using basalt and glass

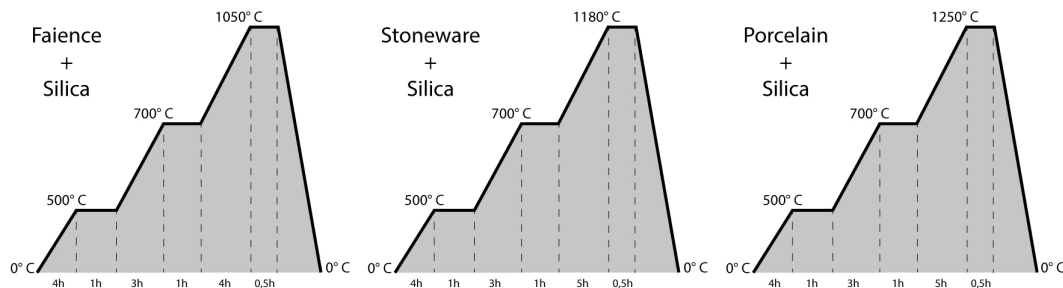


Figure 5.15: Curve temperature of oven using porcelain, stoneware and faience

To demonstrate the temperatures cycles used to reach the sintering stage of the ceramics, Figure 5.15 shows the data related to each material. According with the crystallization behaviour of the ceramics materials was used the temperature of 500°C to stabilize the silica powder, following 3 hours until reach the temperature of 700°C to start the crystallization. Then, the final temperature varies according with the sintering point of each material, being 1050°C for faience, 1180°C to stoneware and 1250°C to porcelain.

5.4 Software of Design Selected

As a prototype machine, the technology of Iro3D is not adapted to computer standard systems, being limited only to the version of Linux Mint 19 Edition Xfce 64 bits. To design the digital models able to be printed, was used the Solidworks software version 2018.

The files formats used to input in the Iro3D slicer software was the STL (stereo-lithography), however the slicer only responds to binary formats. The files saved in Solidworks, even according with the specifications, presents issues when inputted in the program. To dodge this problem, the files were placed in Simplify3D software and saved again in the binary format,

therefore, the slicer can read the STL files correctly.

5.5 Study Case

As complementary studies, the powder grains of the materials was submitted by morphological and composition analysis. In order to improve the knowledge about the material behaviour, is presented the results regarding an analysis of porosity, grain size shape and agglutination.

5.5.1 Powders - Microscopic Analysis

In order to guarantee the best resolution of the images and results, all the powders and parts were submitted to a preparation by coating process.

Using the machine Quorum SC7620 Sputter Coater, represented in Figure 5.16 the samples was coated with a fine layer of gold and palladium, making the visualization of the samples via the microscope viable, more accurate and refined.



Figure 5.16: Quorum SC7620 Sputter Coater. Source: CDRSP-IPLeiria, Portugal.

To testify the veracity of the mineral studied, in case basalt and the other ceramics, in addition to explore new parameters to optimization and performance of the process, the seven distinct materials were submitted to amplitudes of 36x, 50x, 100x, 500x, 1000x and 3000x.

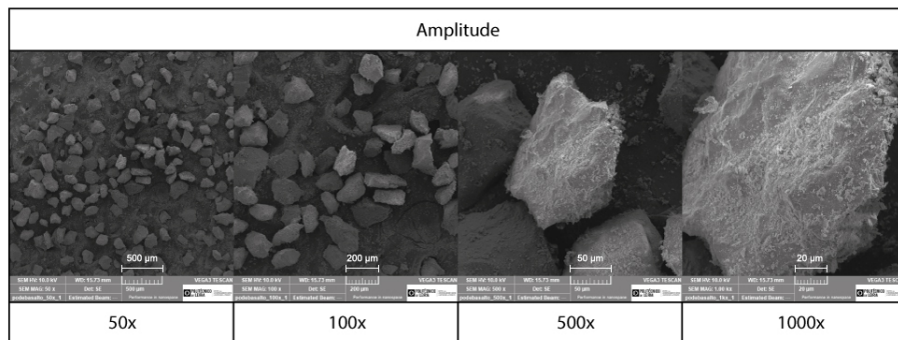
Working with the Electronic Microscope Bruker Nano XFlash Detector 6/30 shown in Figure 5.17, is possible to observe through the images produced the variations of the material



Figure 5.17: Microscope Bruker Nano. Source: CDRSP-IPLeiria, Portugal.

grains and the differences of each material behaviour after the milling and shifting phases.

Table 5.1: Basalt Powder - Analysis and amplitude of the Particles



The results of the microscope shots of basalt powder are represented in Table 5.1. The grain-size powders of 200-299µm present relatively round shapes and flat surface. Consequently the grains show low agglutination with each other, facilitating the dispensation and the flow of the powder.

The faience powder is represented in Table 5.2. In this case, was used to analysis the powders of 63-99µm. The mechanical behaviour of this materials allows a high agglutination rate. Even after several sieving processes, the powder keeps particles of materials dust surrounding the grains. Thereat, the faience tends to agglutinate in bigger pieces, adding this to its non-uniform shape, this material presents issues concerning the grains flow in the nozzles and recharging tubes.

Observing Table 5.5, the glass powder of 200-299µm is presented, having sharp corners and with low dust accumulation rate. In this case, these grains had good performance flowing

Table 5.2: Faience Powder - Analysis and amplitude of the Particles

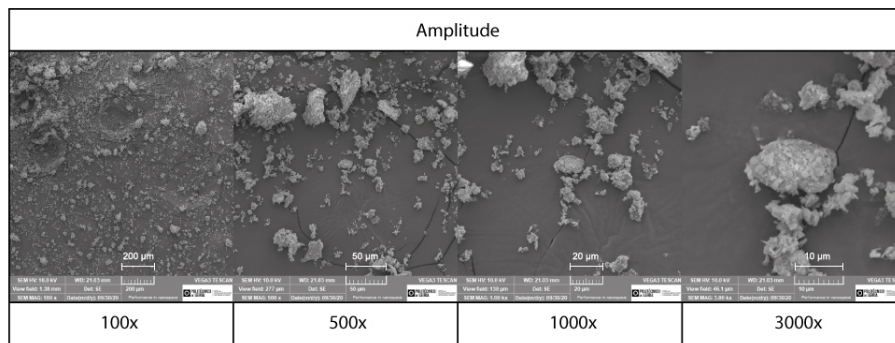
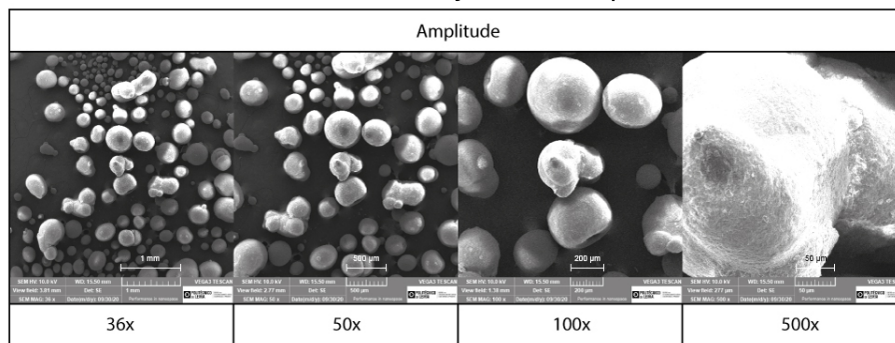


Table 5.3: Porcelain Powder - Analysis and amplitude of the Particles



during the nozzle.

Finally, the silica used to support was analyzed too. In this case, the grains shows a low dust agglutination. This was not a issue in the 200-299 μ m grain-size, however, when applied in different measures such as the others values specified for this work, the agglutination rate increase, difficult the flow performance during the deposition process.

On the other hand, Tables 5.3 and 5.4 shows that grains of porcelain and stoneware have more rounded shapes. This happens due to the efficiency applied on the milling phase. To

Table 5.4: Stoneware Powder - Analysis and amplitude of the Particles

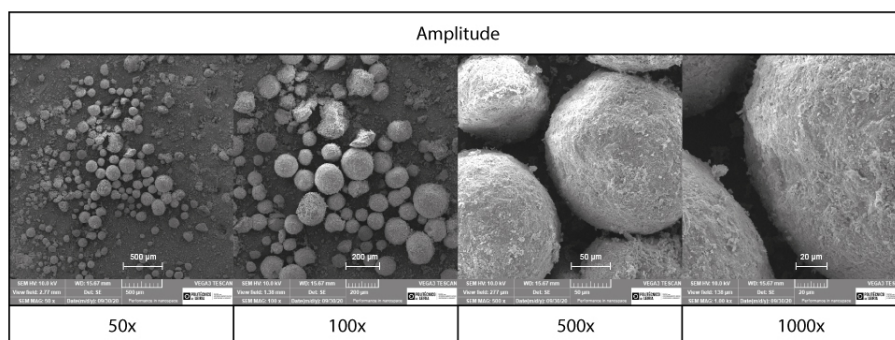


Table 5.5: Glass Powder - Analysis and amplitude of the Particles

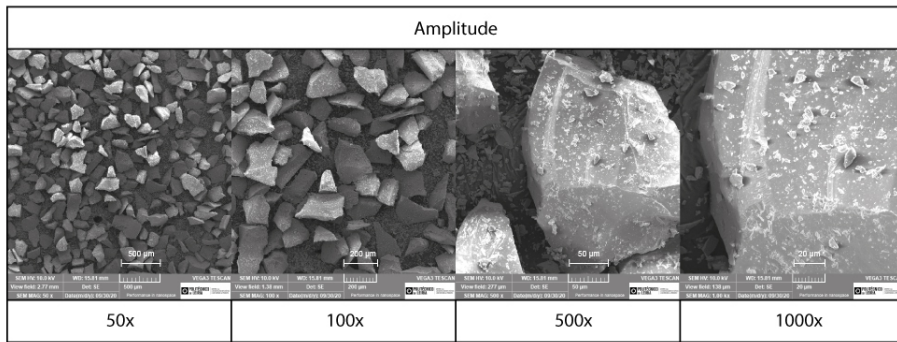
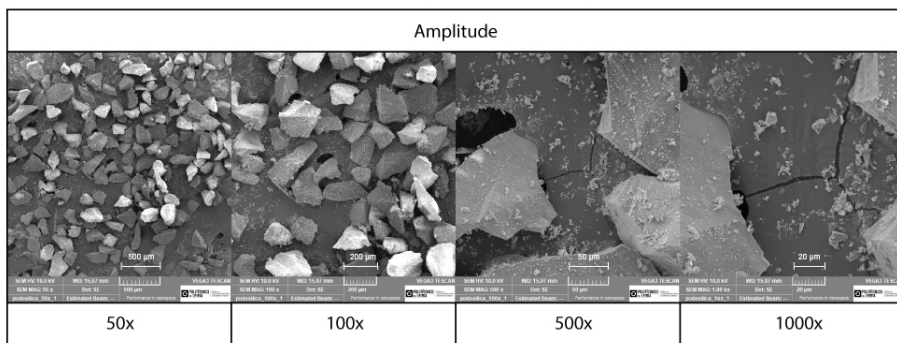


Table 5.6: Silica Powder - Analysis and amplitude of the Particles



the other group of materials, it was used the raw material and its shape was formed through the previously cited steps, being milling and sieving manually. In the case of porcelain and stoneware, the powder was provided in grains of $\leq 300\mu\text{m}$ and was milling industrially by the provider.

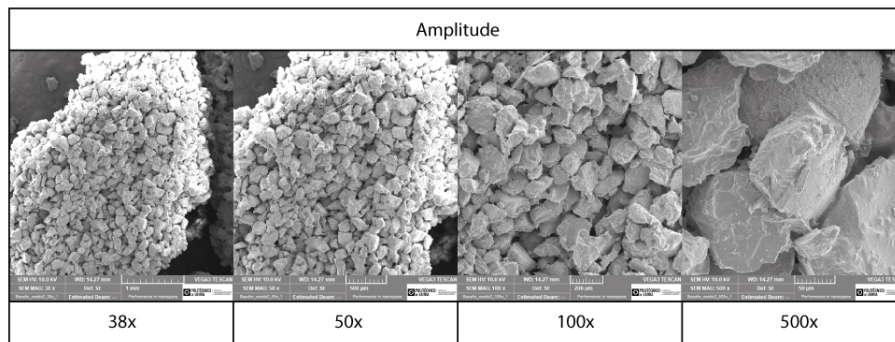
5.5.2 Morphology Analysis - Microscope

To certify and prove the sintering capacity of basalt, a first initial test was carried out to explore and analyze how morphological changes in the particles of the material.

In this way, to create the first samples, it was applied manually and deposited an amount of basalt inside a crucible and coated laterally with silica. For the tests carried out, the same grain sizes of 200-299 μm were used for all the samples. It was used as an open mold strategy, without layers of silica on top, to evaluate the behavior of material transformation under temperatures of 1200°C, 1250°C and 1300°C.

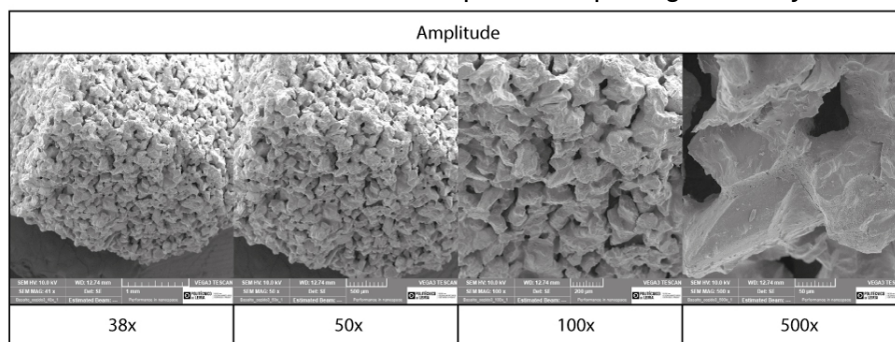
In the context of seeking more depth on this topic, the molecular structure of the part of the post-cooking basalt test is presented. In this study, it is demonstrated that it evaluates and confirms the sintering capacity of basalt and its molecular composition.

Table 5.7: Sintered Basalt Sample 1. Morphological Analysis



The results obtained show that in the lowest temperature of 1200°C, the basalt does not fully sintered, being stable in the initial stage. As presented in Table 5.7, the first sample revealed that at this temperature, not enough energy is generated for the total deformation of the grains, causing them to not be completely stuck with each other and preventing the formation of a single solid parts. Consequently, the piece of basalt presents agglomeration and creates a shape, but ends up being fragile, falling apart when touched, not being adequate to handling functions.

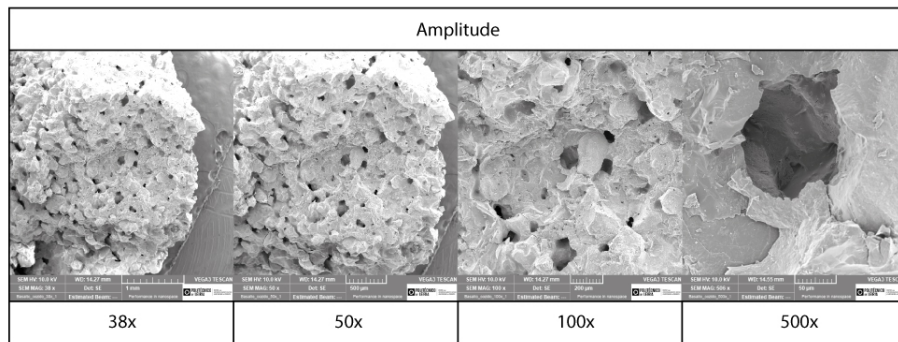
Table 5.8: Sintered Basalt Sample 2. Morphological Analysis



In Table 5.8, is possible to observe the morphology of the basalt part sintered in a temperature of 1250°C, reaching the intermediary stage o sintering. This sample presented the best parameters regarding the morphology and final appearance of the part. The particles stay fixed together and the strength and resistance becomes acceptable without burn marks or falling apart.

In sample 3, Table 5.9 present the structure of the particles submitted to a temperature of 1300°C. In this case, more connections between the particles provided a part with less porosity. The temperature morphology stays closed to melting state.

Table 5.9: Sintered Basalt Sample 3. Morphological Analysis



5.5.3 Composition Analysis

To demonstrate the elements those compose the basalt material, the powder and the same first assay was submitted to an composition analysis. The main elements that compose the basalt is silicon (Si), oxygen (O), aluminium (Al), magnesium (Mg) and carbon (C). In addition, the results founded small quantities of calcium (Ca), potassium (K), sodium (Na), iron (Fe) and titanium (Ti). In Figure 5.18, the chart illustrate the big amount of silicon, oxygen calcium and aluminium.

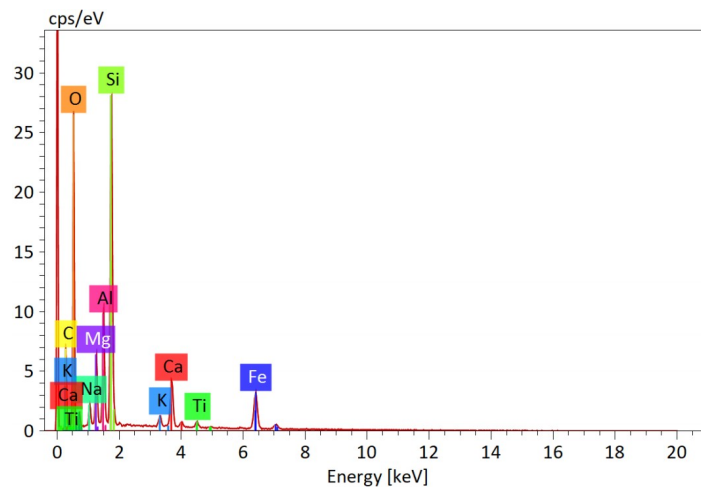


Figure 5.18: Basalt powder composition chart.

To have a better exemplification of the composition of the powder, Table 5.10 shows the result of the composition analysis.

After submitted to the sintering process, the behaviour of the material demonstrated differences in the chemical composition. Is possible to observe in the chart illustrated in Figure 5.19 that the levels of oxygen becomes higher in the same way that silicon and aluminium decrease. The elements such as iron and potassium also presents increase in its amounts. Sodium and magnesium does not present significant relevance, instead of titanium that practically disappears, represented by 0.29% of the mass, as shown in Table 5.11.

Table 5.10: Basalt powder composition.

Basalto em po 273

Element	At. No.	Netto	Mass [%]	Mass Norm. [%]	Atom [%]	abs. error [%] (3 sigma)	rel. error [%] (3 sigma)
O	8	36872	30.61	50.69	65.64	11.17	36.49
Na	11	2853	1.38	2.29	2.07	0.37	26.92
Mg	12	10541	3.43	5.67	4.84	0.66	19.25
Al	13	18510	5.13	8.49	6.52	0.83	16.16
Si	14	59923	13.18	21.82	16.10	1.77	13.46
K	19	2791	0.55	0.91	0.48	0.14	25.00
Ca	20	11904	2.35	3.90	2.02	0.29	12.52
Ti	22	1575	0.32	0.53	0.23	0.11	35.29
Fe	26	11281	3.44	5.69	2.11	0.37	10.74
		Sum	60.39	100.00	100.00		

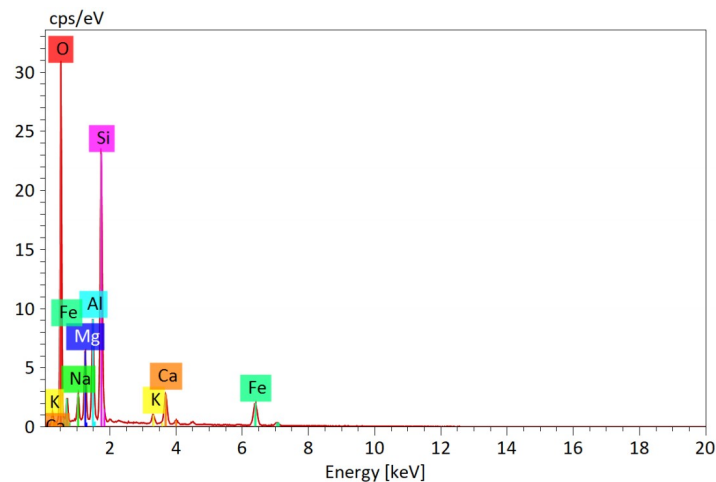


Figure 5.19: Sintered basalt part composition chart.

5.5.4 Porosity Analysis

To look closely into the results on sintered basalt, the first sample sintered in 1200°C was submitted to a computed tomography on Bruker SkyScan 1174 machine shown in Figure 5.20. It is a lightweight micro-CT device used in applications for material science, industry and biomedical, and for quality control.

A two-dimensional projection of a three-dimensional object is represented by an X-ray image. In this case, each point in the image includes the integration of the absorption information along the trajectory of the partial X-ray beam inside the three-dimensional object. Using an adjustable voltage X-ray source, computed micro-tomography is a 3D radiography, being small-scale and with improved resolution, just like hospital tomography.

Basalt gathers iron and magnesium in your composition, because of that, was not easy to get the images in good resolution, due to excessive reflection rate and interference that spoiled the results. To dodge this problem, an aluminium filter of 0.5µm was used to get a better resolution of the part.

Table 5.11: Sintered basalt part composition.

Basalto cozido 272

Element	At. No.	Netto	Mass [%]	Mass Norm. [%]	Atom [%]	abs. error [%] (3 sigma)	rel. error [%] (3 sigma)
O	8	50551	40.02	56.39	70.12	14.22	35.52
Na	11	4887	2.39	3.37	2.91	0.57	23.80
Mg	12	12888	4.27	6.02	4.93	0.80	18.70
Al	13	19767	5.58	7.87	5.80	0.89	16.01
Si	14	57342	12.68	17.87	12.66	1.71	13.48
K	19	2695	0.59	0.83	0.42	0.14	24.18
Ca	20	9120	2.08	2.93	1.45	0.27	13.11
Ti	22	830	0.21	0.29	0.12	0.10	50.64
Fe	26	8556	3.15	4.44	1.58	0.35	11.13
		Sum	70.97	100.00	100.00		



Figure 5.20: Bruker SkyScan 1174 - Micro-CT machine. Source: CDRSP-IPLeiria, Portugal.

According with the tables and results, the part of basalt printed used 200-299 μ m grain-size, baked in a temperature of 1200 $^{\circ}$ C, showed a big part of porosity in the composition of the sample. This temperature represents the initial state of sintering, when the grains are not completely fused with each other and the porosity rate is high.

The results presented show the part after exposed to X-ray. In Figure 5.21, the red rectangle, corresponded to the area of the sample was to be analyzed. Is possible to observe the white points corresponding to the material, while the dark area represented the air inside the part. Is possible to observe in this figure that the particles tends to be more agglutinated in the extremities of the part, creating more resistance and hardness on this areas. On the other hand, in the same way, the center areas of the part became more soft and fragile, because these areas had a big amount of air, generating an high porosity rate in these areas, reaching the value of 60% of the part. To have a better understanding of how this particles are distributed and how the porosity works, check Tables 5.7 and 5.8.

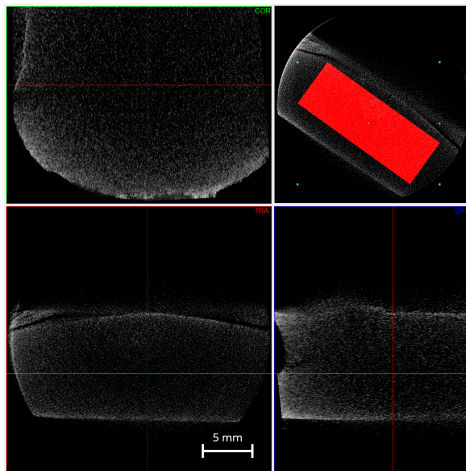


Figure 5.21: Basalt part in micro-CT.

Chapter 6

Results

During this chapter, the results acquired after the steps and procedures listed previously will be presented, as well as the difficulties found during the process, regarding the machine, material and shapes. In the further sections, the results corresponding to the production process of selective deposition of powders will be presented through the Iro3D digital powder selection system.

6.1 Analysis Process

In this section, the results corresponding to the production process of selective deposition of powders will be presented through the Iro3D digital powder selection system. Here, we will see the greatest difficulties and challenges faced to achieve the results disclosed below. The process used to print the pieces has interesting characteristics in terms of producing ceramic pieces in an alternative way to traditional production concepts. By applying the powders in a selected way, the process is able to guarantee the position of the part to be produced, as well as wrap the support material and seal it with it so that it can go to the oven.

6.1.1 Process

During the selection of materials, several of them had difficulty in remaining in good condition to be applied. As previously mentioned, the problem related to the absorption of moisture by the powders proved to be a constant obstacle during the process, making incubation and resting in the greenhouse necessary at all stages for the storage of the powders. In addition to not dripping, powders tend to adhere to the locations of work areas, tools and machines.

It takes a relatively long time to produce the parts, since it is necessary to keep powders in greenhouses for at least 1 day in advance, in order to guarantee the removal of all moisture presented in them.

From the moment the printing starts, the time varies a lot depending on the shape and size of the chosen piece. Thus, considering the rectangles and test pieces with the measurements presented above, the average printing time for each piece was around 13 hours.

After printing, the materials were submitted to the compaction process. In the case of basalt, for example, there was no need to include water, since the type of material did not absorb it. However, when dealing with ceramic materials, the use of water together with pressure showed the best result. Therefore, it was necessary to rest them in the oven to remove moisture again. As the amount of water needed was small, a period of 6 hours in the greenhouse was enough to guarantee a better compaction and removal of the moisture.

After these steps, the pieces were placed in the oven for the sintering process to take place. Respecting the cycle defined for each material, the cooking time could take up to 14h, depending on the characteristics of each one.

Comparing with other AM processes, which are considerably longer than conventional production processes, the DSPD process takes even longer, making the time for the production of each piece with the shapes and measures defined for this project be it in an average of 3 days, presuming that no other setback would occur.

6.1.2 DPSP on Iro3D Review

The Iro3D machine demonstrated in Figure 6.1 an alternative concept for the production of parts from the DSPD process and effectively managed to produce parts with certain precision when using metallic materials.

In the case of ceramics, performance showed to be different. Speaking only in the case of the materials studied, powders ground manually or using a simple grinder demonstrated difficulty in running through the mechanisms, both through the nozzle and through the supply tubes. As a consequence, at some point in the process, all materials presented difficulties in being worked in a totally efficient way. Whether due to the shapes of the grains or the physical properties of the materials, the powders that had a high agglutination rate constantly clogged the deposition outlet, thus making printing impossible, except for materials that were milled industrially, presenting grains of more round shapes that could flow better.

The main mechanism composed of several components, responsible for transporting and supporting the nozzles from the deposition area to its base, also had the function of ensuring the deposition of the powders and the orientation of the Z axis, producing the layer-by-layer process, depositing the amount of powder corresponding to the layer height delimited in the slicer. This mechanism, contained a motor that was responsible for turning a gear that was well designed to go down and fit in a pulley connected to a thin vertical tube that went

straight to the nozzle exit hole. Connected to the same piece, a vertical bar pressed a lever attached to the nozzle boxes, causing this tube to rise and release the outlet for the powder to drain. Both movements were essential for the deposition of the powders, making their performance satisfactory when working properly. The engine used in the gear that spins the thin tube appears to be efficient, but its power and durability is questionable, since it can fail when used very often, making it worthwhile to evaluate the replacement with a more powerful one that would not force it as much, preferably respecting the dimensions established by the structure design.



Figure 6.1: New Iro3D model. Source: CDRSP-IPLeiria, Portugal.

Considering that it is a prototype and conceptual machine, its structure of the axes, motors and sensors appears to be considerably elaborated, as well as its intelligence in reading and reproducing the trajectory codes established for guidance. Its displacement and movement are precise and considerably fast when it is traveling outside the deposition process, however, as a safety system, any force applied against its programmed direction causes the machine to stop immediately, ensuring a system for preserving the components that, in certain situations may prove to be an inconvenience.

Another problem found related to trajectory, is the deposition of the material that acts as a coating for the main powders that will form the pieces, which are deposited by nozzles 0 and 3. In addition to presenting greater difficulty in relation to the fluidity of the powder, it is observable that its orientation is out of alignment with the position of the piece, causing it to be deposited in a place that is not supposed, not having the correct efficiency. This is due to bugs in the performance of the slicing software, which still needs improvement.

The machine and slicer are not compatible with standard systems, being developed to work only with the Linux Mint 19 Edition Xfce 64-bit system, limiting its use to be possible by the widest range of users. Some problems of unusual translation in the configuration parameters, end up also hampering the exploration of new printing standards and analysis of performances.

The initial printing phase must also be carefully observed. Several times it happens to

fail to reproduce the first layer and start directly with the second, which interferes with the formation of the piece, since the initial layer is responsible for ensuring the heat insulation and avoiding the contact of the piece with the crucible. With this failure, the part does not form correctly, causing the part to become stuck in the mold, impacting its shape and surface finish.

Finally, it is necessary to improve the supply system. As already mentioned, the powder has difficulties to flow from the tubes that connect the storage compartments to the nozzles. Also, when is necessary to recharge, the main structure brings the nozzle to the base, elevating few centimeters to move a lever that liberate the powder flow. However, the amount that is deposited in the nozzle, often is less that the amount deposited to produce a single layer, that occurs because the lever mechanism is not well calibrated, being in some times not effective to supply.

6.1.3 Basalt

As the main material and focus of this project, the results are presented according to the parameters established for the analysis of composition, morphology, resistance and performance of the process. Observing the behavior of this mineral, basalt showed great differences in terms of temperature. This being an essential factor for the success of its sintering and acquisition of the final form.

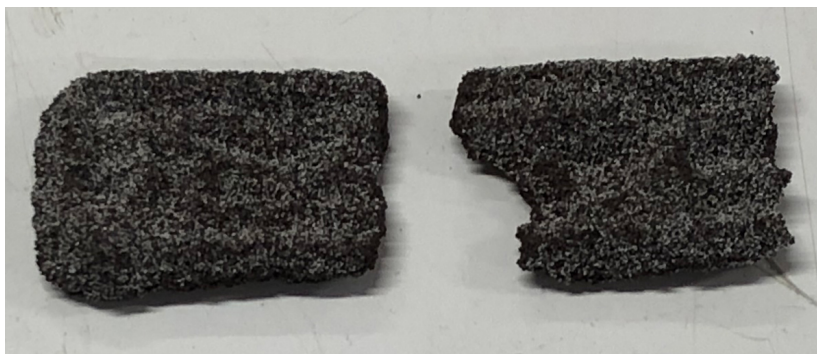


Figure 6.2: A fail part of basalt, rectangular shape.

With temperatures of 1200°C, the basalt reach the initial sintering state, showing low agglutination rate, having difficulties even to maintain the desired shape, either of rectangle or specimen. Not reaching the sintering of the particles completely, the desired shape became fragile to the point of being slightly broken by touch. With a darker shade, the Figure 6.2 and 6.3 shows that the basalt cannot maintain its complete shape and can not be submitted to tensile or flexural tests, and did not present resistance in the parts that formed. Its surface finish is not relevant, as it falls apart when handling with more pressure.

By increasing the temperature to 1250°C the sintering process is more efficient, reaching



Figure 6.3: A fail part of basalt, sample shape.

the intermediary state and creating a firm and resistant part. Unlike the previous case, the pieces did not show deficiency in merging, maintaining considerably the desired shape. The surface finish remains rough, but rigid, as you can see in Figure 6.4 the shade becomes lighter, closer to brown, without showing burn marks or fragility in the morphological structure.



Figure 6.4: Basalt - using silica as support and pressed before cook

Where the final temperature was 1300°C, the structure of the part was completely rigid, forming a totally rough surface with a dark brown color. In this case, it is possible to notice darker burn marks in some regions of the piece. Especially in the upper area, it is possible to visually perceive in Figure 6.5, structural differences in solidification, rigidity and change in shape, due to reach the final sintered stage, close to melting point, reducing the density and compacting the material and losing the designed shape. Thus, the better conditions found to proceed to the tensile analysis was the intermediary sintering state.



Figure 6.5: Basalt - using silica as support

Considering the evaluation temperature tests and to bring a better understanding of the

material behaviour, Figure 6.6 shows the morphology of the pores inside of the material beam. In this new perspective, it is possible to verify that different reactions occur in distinct areas on the same part. The external area becomes more compact and presents less pores than the internal area, where few pores still remain present, although its structure keeps rigid and resistant.



Figure 6.6: Inside structures of basalt sintered.

Mechanical Properties

In the case of basalt, rectangular parts were produced to facilitate the bending analysis. To presents the shape accuracy of the parts produced, according to Table 6.1, is possible to observe that the basalt produced parts have a contraction of up to 22% of length and 30% of width, comparing with its original shape designed. On the other hand, the height of the parts got an increase in up to 50%. This occurs according to the mechanical behaviour of the materials sintered.

Table 6.1: Measures of sintered basalt.

Sample Basalt	Length (mm)	Width (mm)	Thickness (mm)	Area (mm ²)
1	61,03	16,76	6,80	113,97
2	58,09	16,50	7,40	122,10
3	55,82	15,98	7,50	119,85
4	59,15	16,79	7,46	125,25
5	59,16	16,6	7,38	122,51

To calculate the tensile strength and yield, in same way of force applied and displacement, the tensile machine was used to submits the samples to a bending test. As the basalt has the chemical composition similar to glass, being composing mainly by silicon, the parameter consider to make the tests was according to the norms applies to the ceramics materials in ambient temperature, containing in the ASTM standards (Designation: C1161:13)[33], when the velocity used was 0.7 mm/min.

Illustrating how the test works, is demonstrated in a Figure 6.7 the variables considered for the parts submitted to a tensile force applied on bending.

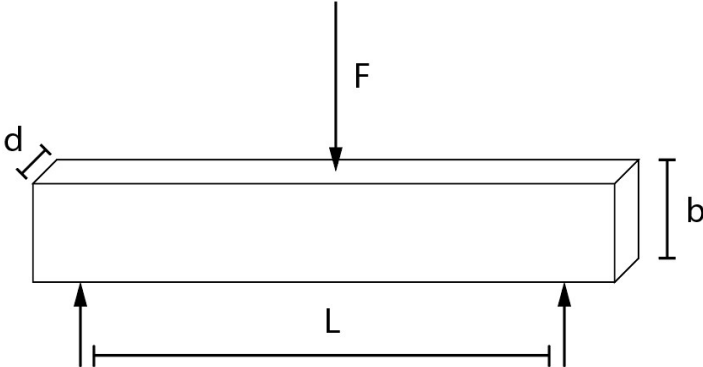


Figure 6.7: Tensile test applying on bending.

When F is the load applied on the middle of the part, b is the height, d is the width and L is the distance between the two supports beams. For this test the value of L was considered 37 mm.

Using the values provided by the machine, was generated a chart to exemplify the behaviour of the material when submitted to an flexural load. In this chart shown in Figure 6.8, is possible to see that the curve presents variation on its constancy, due to the behaviour of the sintered grains that compose the beam, once that these grains were not as resistant as fused materials.

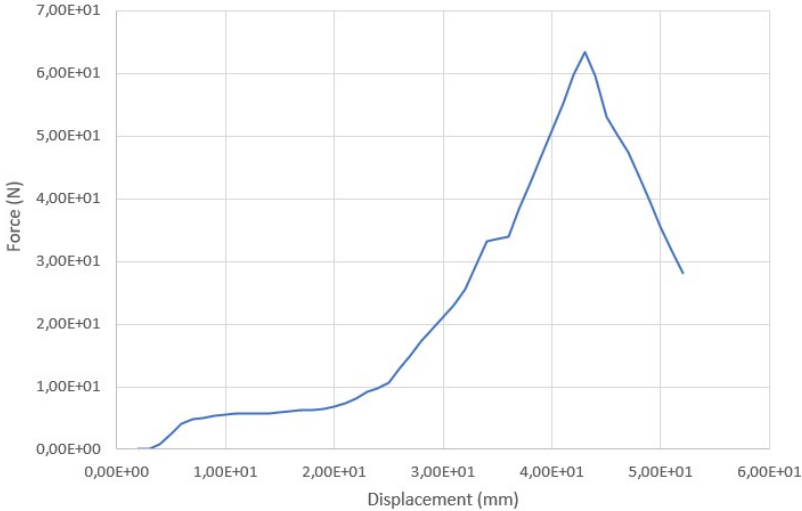


Figure 6.8: Function force-displacement chart of basalt sample 4

In this case, the formula used to calculate the tensile strength is described below:

$$\delta_{fs} = \frac{3F_f L}{2bd^2} \tag{6.1}$$

Calculating the measurements applied to the mechanic properties of the sintered basalt, the results are provided in Table 6.2.

Table 6.2: Mechanical properties of sintered basalt.

Sample Basalt	F _{max} (N)	σFS (MPa)	ε (mm)
1	73,03	5,23	1,83
2	53,83	3,30	2,93
3	53,53	3,31	2,52
4	64,80	3,85	1,07
5	80,03	4,91	1,36

6.1.4 Glass

The powder glass was subjected to a temperature of 900°C and the preliminary essays of glass were considered promissory. The morphology was well defined, such as agglutination, strength and shape.

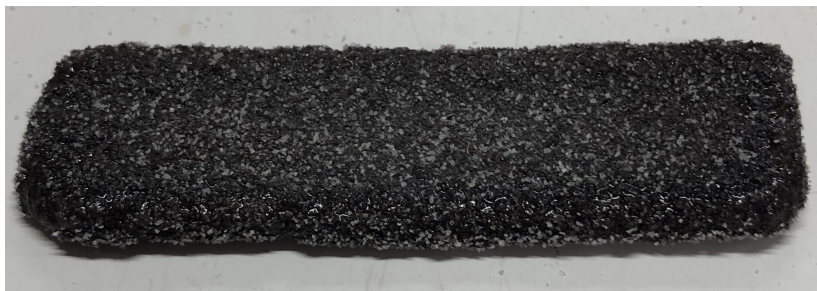


Figure 6.9: Glass part with water reinforcement, bottom view.

It can be seen in Figure 6.9 a sample made using silica with water and pressure reinforcement for agglutination. This sample shows good results for sintering and surface stability, it also showed good resistance to tension and impact regarding its material limitations. Its structure presents rigidity to the handling and good preservation of the form with slight deformations.

Through the reinforcement with pressure and water, is shown in Figure 6.10 that the base of the samples becomes flatter than the superior area, due to the contact with the silica powder pressuring against the crucible. Thus, the surface that has contact only with the silica powder cover, even using a flat surface for doing the pressure, has more variation that the inferior.

Inside the interior of the sintered glass sample, a unexpected result was obtained. Figure



Figure 6.10: Glass part with water reinforcement, top view.

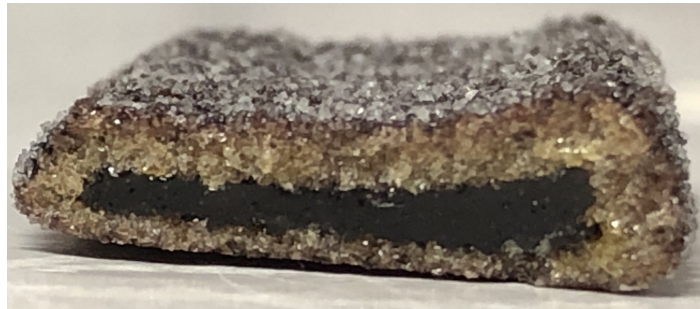


Figure 6.11: Fractured glass part

6.11 show that the sintering of the material occurred on the external cover of the part and was well defined, while inside it reached the melting point, becoming crystallized and more resistant.

Mechanical Properties

Using the same evaluation parameters of the basalt material, considering the mechanical properties of the glass, the results found derived from the flexural tests is presented next. The measures of the results concerning the shape and structure of the glass samples is described in Table 6.3.

Table 6.3: Measures of sintered glass.

Sample Glass	Length (mm)	Width (mm)	Thickness (mm)	Area (mm ²)
1	65,07	18,63	5,63	104,90
2	64,05	17,98	5,89	105,90
3	64,85	18,55	5,52	102,40
4	64,70	18,31	5,55	101,60

According to the table and considering the original shape, the sintered glass presents a reduce of up to 9% of length and its height a increase of up to 17%. The most affected measure was the width, with a decrease of 22%. This measures present a small variation

comparing with the basalt.

The chart illustrating the function of force-displacement curves of the glass to exemplify its behaviour submitted to tensile test is presented in Figure 6.12.

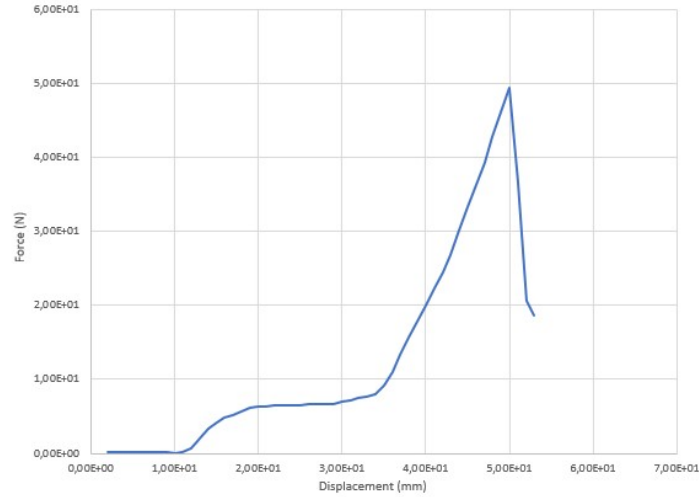


Figure 6.12: Function force-displacement chart of glass sample 3

The same formula (6.1) was used to calculate the tensile strength of the sintered glass. Table 6.4 provide the data related to the results of the mechanical properties analysis. As brittle materials, basalt, ceramics and glass, have a yield strength similar to the failure point.

Table 6.4: Mechanical properties of sintered glass.

Sample Glass	F _{max} (N)	σ _{FS} (MPa)	ε (mm)
1	73,98	6,95	3,60
2	49,23	4,38	3,52
3	50,85	4,99	3,30
4	84,05	8,27	3,81
5	54,60	5,09	3,36

6.1.5 Ceramics

In the case of ceramics, the tests showed variable results. The aiming was to explore the capacity of sintering and agglutination strategies of the selected materials. As previously mentioned, it was not possible to use powders of 63-99µm and 100-199µm grain-sizes due to their difficulty in flow through the tubes connecting to the reservoir and the nozzle deposition orifice.

Starting with faience, which was the material most affected in this process, not even the size of 200-299 μm powder grains can flow efficiently. Due to its high agglutination rate, the faience powder, even after being submitted to the greenhouse several times, did not show good flow and always remained clogging the spout. This is due to the grain-edged shapes and their static conductivity, making the grains tend to agglutinate as shown in Figure 6.13, into larger groups preventing the flow of the powder.



Figure 6.13: Faience powder

In porcelain and stoneware, the parameters change, since industrially ground powders in round grain formats were used. These powders showed excellent fluidity and allowed the production of parts with sizes of 200-299 μm . In the regular process of both ceramic materials, without any preparation before cooking, when subjected to a temperature of 1180 $^{\circ}\text{C}$, the samples presented in both open and closed mold, low sintering rate in their morphology. Not being able to maintain its original shape and presenting weak resistance and hardness, the pieces showed to be very fragile and fall apart during handling, as can be seen in Figure 6.14.



Figure 6.14: A fail part of porcelain, using silica without reinforcement

Even using simpler formats, reinforcement is necessary to achieve quality with ceramic materials. Without it, sintering the part occurs with difficulty generating deformations and complications related not only to the surface but also to the precision of the shape, as can be observed in Figure 6.15.

However, the porcelain powder being applied through the closed mold with a reinforcement of compaction with water and pressure, showed good results regarding the morphology of the material. Its surface became more rigid and uniform, maintaining the original shape of the part, as you can see in Figure 6.16. However, it proved to be fragile and presents slight decomposition during handling.



Figure 6.15: A rectangular part of stoneware, using silica without reinforcement



Figure 6.16: A rectangular part of porcelain, using silica with water reinforcement

Using the same temperature, water and pressure parameters of the last sample, a test was performed with the mold open. In this case, there was a greater deformation in the result, since by wetting and pressing the piece with the grains still loose and without the silica above to protect, it can change the way they are deposited. Despite being in an open mold, the sample showed no difference in terms of strength and sintering, but it presented a smoother surface, due to pressing with direct touch on the material, as shown in Figure 6.17.

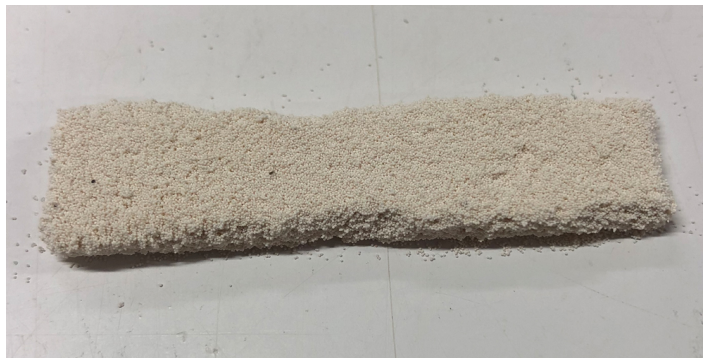


Figure 6.17: A rectangular part of porcelain, using silica with open mold

In order to better represent the difference in quality related to the preservation of shape, using the water and pressure strategy, we can see in Figure 6.18 and Figure 6.19 the morphological difference reached in the result. Often, without the reinforcement, the grains of the ceramic powders tend to have sintering failures, damaging the structure of the part.

Finally, the Figure 6.20 presents the inside area of the stoneware after the sintering pro-

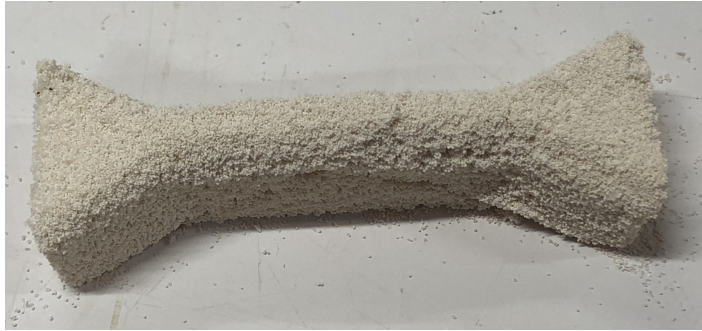


Figure 6.18: Shape and formation difference, without reinforcement



Figure 6.19: Shape and formation difference, with reinforcement



Figure 6.20: Fractured stoneware part.



Figure 6.21: Fractured porcelain part.

cess without any reinforcements. In this case, the porosity of the material and its poor compaction is more intensive inside. On the other hand, the part made by porcelain with water and pressure reinforcement shows be more structured, maintaining the part more uniform in its morphology as presented in Figure 6.21.

6.2 Synthesis for future oriented design.

Based on the considerations made in the review section of Iro3D, a new design for the nozzles is suggested. Thinking about the difficulties encountered, an optimization was developed that aims to improve the performance of the deposition of the powders.

Introducing a vibration system, Figure 6.22 presents a new design for the nozzle, reformulated in order to adapt the vibrators to ensure the flow of the powder. The use of vibrators has already been studied to improve the parameters of use and has shown good results, considering the compaction and dilation behavior of the powders [34].

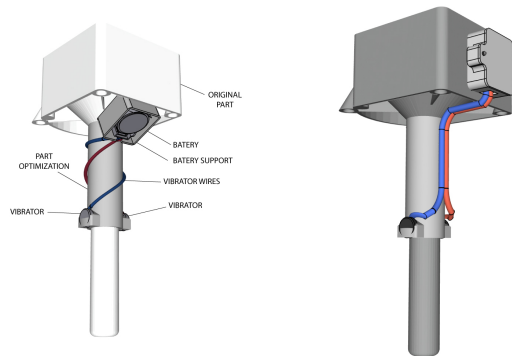


Figure 6.22: New optimized model with vibrators

With this, two mini disk vibrating motors, similar to those of cell phones, were used to perform this function. With diameters of 10mm and thickness of 2.7mm, and variable in voltage from 2V to 5V, these vibrators can reach 11000 RPM at their maximum voltage, being able to guarantee the fluidity of the powder without causing damage to the sensitive deposition tube.

To reinforce the resistance of the tube and guarantee the minimum of harmful impact, the walls where the vibrators would be positioned were reinforced with an additional 2 mm of thickness. In addition, two support structures were designed to position and maintain the vibrators in the correct positions.

To avoid the excess of unnecessary wires that hinder the performance and aesthetics of the machine, a box for simple 3V lithium cell batteries was included in the back of the nozzle material storage box, considering the suitability for the measures and the fit in the

main transport structure of the machine.

Chapter 7

Conclusion

In this section, the conclusions related to the entire process and its results will be presented. The focus of this work was to establish an exploratory process to study the performance and feasibility of selective deposition of powders in conventional ceramic materials, in basalt and glass, materials that are little explored in AM processes. Considering the studies presented and based on the analysis and tests performed, we can say that the materials chosen for this project have promising prospects according to the DSPD processes.

One of the biggest challenges found in this project was to adapt the material powders to the deposition system used by Iro3D. Many difficulties were encountered in relation to the flow of powders through the nozzle and in the refill tanks. Due to the high agglutination rates of the grains during their storage, the grains tend to accumulate in the exit orifice for deposition, constantly clogging and preventing the flow and movement of the powders, limiting the powders with grains sizes, as the only option for study of 200-299 μm .

Because of this, a solution for the optimization of the deposition system was necessary, to improve the flowing of the powder, through a vibration system coupled to the nozzle, allowing, in theory, better flow and use of conventional powders and others with established sizes.

The storage of powders in greenhouses with a temperature of 60°C, demonstrated good efficiency in improving the flow of the powder, removing moisture and allowing the grains not to agglutinate into larger pieces, improving the dynamics of the movement of the powders by the depositor.

Another difficulty encountered was in relation to the slicer software of the Iro3D system. In addition to the machine not working with standard systems normally used in the market, it presents several bugs in its operation, the values must be placed according to references already used in past experiments. These bugs are present during the introduction of several important parameters for the performance of the process, from the application of values such as layer height and speed to the difficulty in interrupting production. An upgrade in software programming is something to be considered for improvement in the future.

In relation to the developed parts, the samples of basalt and glass, presented good resistance and morphological composition, in addition to respecting considerably the dimensions and shape of the proposed design. Thus, it demonstrates a good opportunity to explore applications and concepts relevant to the materials engineering area.

The ceramic materials, on the other hand, presented a good perspective, but with the need for further testing and possible applications for their use, demonstrating good sintering behavior and shape preservation, at the same time as fragility and low resistance. However, its high variation of materials with similar characteristics allows the exploration of new strategies for the production of parts using two or more materials during the same process, reaching new parameters for the production of ceramic parts.

Chapter 8

Future Expansionary Potential

Finally, the basalt is a material that is found in abundance, mainly in islands such as Iceland, Hawaii, Azores, Cape Verde and other volcanic islands. Not restricting to the Earth, it is also possible to find basalt in others components of the solar system, such as the Moon, Mars and Venus, as well as asteroids that circulate in the belts between the planets, opening a spot for their future potential, regarding to the technological development in the ocean and space explorations.

In order to demonstrate the capabilities and perspectives for the use of this material, considering its efficiency, resistance and availability, several studies have demonstrated great efficiency in exploring the characteristics of basalt for different areas. From regolith to the construction of materials for large-scale additive manufacturing such as houses and architectural environments in space stations on other planets [26].

In addition, basalt fibers demonstrate good mechanical behavior in terms of hardness, thermal conductivity, lightness and electric insulator, among others [35], being a material that may become essential in the future.

Combined Materials

Searching to expand the limits of use for materials, a preliminary experiment was made combining two ceramic materials with similar sintering points in the same printed part.

This experiment aimed to certify the possibility of using different materials that present similar behaviors and specifications, applying the powders of these materials selectively in established areas.

Slicing the part in two equals layers, superior layer was made with porcelain and the inferior layer with stoneware as shown in Figure 8.1, a sample was built with this two types of ceramics. Considering the results presented previously, the built part was submitted to tem-



Figure 8.1: Explore the limits using porcelain and stoneware combined

perature of 1250°C been this one the highest temperature concerning the material parameters. In this case, the machine was not well adapted to deposit different mainly materials. To proceed with the essay, the powder of stoneware was deposited manually in the superior layer. Consequently, this part was produced using a open mold without any reinforcement methods.

As a result, the stoneware layer became more rigid and preserved the shape designed. This happens due to high temperatures at which it was exposed to. On the other hand, the porcelain layer presented the same weakness concerning the open-mold method without reinforcement. The morphological structure was not successfully done, generating deformation, fragility in the part and not reaching the desired shape.

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