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MODULE 1
Additive Manufacturing

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1.1. The Importance of Industrial Design

CONTENTS

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1.1. The Importance of Industrial Design

In this part, the term industrial design always has the meaning of product aesthetics, and the two terms will be used interchangeably.

The world market experiences a constant evolution in the economic, financial, political, social, and technological system, which puts industrial design at an advantage. This evolution is characterized by the following processes:

- generalized globalization (very few territories are not affected by the economic influence of some companies and organizations located even many thousands of kilometres away);
- fierce competition (to acquire a cutting edge, companies invest large funds in different directions, such as technological, marketing, etc.);
- accelerated technological progress (high-level technologies launched by large companies become technically and financially accessible to medium and small companies in just a few years);
- the generalization of quality systems (very few companies and organizations today "afford" not to invest in the development of an effective quality system);
- the sophistication of the public (each market segment or niche wants products precisely tailored on its needs, expectations, and desires).

The result of this market evolution is twofold:

- A company's competitors have an almost identical product on the market with the same guaranteed quality and with an approximately equal price.
- Potential customers want to be able to choose the right product quickly and easily for themselves. They can make the product choice based on brand awareness and industrial design [1].

What was presented above has shown that industrial design is important. But how important is it? Is it equally important for all product classes? A research [2] carried out taking into

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account the Locarno Classification indicated that industrial design is most important for personal and family products, because product aesthetics act as a vector for personal and family own values. In the second category of importance were the products used for professional purposes, and in the last - the products employed for hobby and smoking. These are just guidelines to estimate the importance of industrial design and every product manager and every design representative in top management should perform her/his own research to assess the importance of industrial design attributed by her/his market segments in order to know how much to invest in the development of product aesthetics.

1. *Industrial Design – Vector for Product Meaning*

It is widely assumed that industrial designers create product aesthetics according to their own will and inspiration. There would be no constraints and no objectives. This assumption is wrong, because the industrial designer has the task of attributing the product a certain meaning through its shape, colours, textures, and details. The product meaning is established by the manufacturer and is in agreement with the values, expectations and characteristics of the market segment targeted by the manufacturer. For example, a production company targets a market segment characterized by mature age, high education level and high income, and as human values – respect, tradition, and sense of accomplishment. Consumers belonging to that market segment will want that product to respect (to some extent) tradition, look appropriate for their age, and visually indicate quality and even luxury. At first sight, conferring the required meaning by means of product aesthetics seems difficult and complicated. Things are greatly simplified by the application of communication theory in industrial design.

The ***communication theory*** assumes the existence of a sender who emits a message. The message expresses a certain reality, called context. Depending on the properties of the medium through which the message is transmitted, an adequate message encoding is carried out (with the help of a transmitter) in codes capable of being transmitted through that medium to the destination's receiver [3]. The transmission of codes can be disturbed by noise,

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preventing the receiver from decoding the message to make it accessible to destination. Therefore, decoding should detect and correct possible errors. Ideally, the initial message should be identical to the one that reaches the destination. In order to achieve this, it is necessary that the decoding process should be exactly the reverse of the encoding process, and that the transmitted codes are appropriate for the medium through which the message is transmitted. All three processes (encoding, transmission, decoding) can be affected by noise from outside the environment (Figure 1).

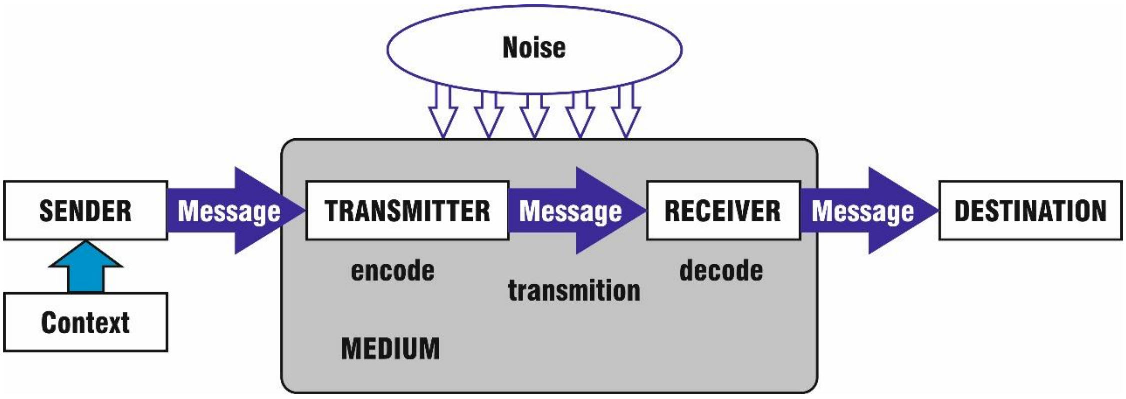

Figure 1. Communication Theory [3]

In industrial design, the communication theory is transposed as follows (Figure 2): The industrial designer formulates a message about a certain context (for example, about the values and expectations of the market segment). She/he encodes the message using the product language elements, namely the product shape, its colours, etc. The message is perceived and decoded by the human sensory organs and the areas on the cerebral cortex associated with them. Decoding and, above all, understanding the message causes the user / observer to react. Reactions can be: a) cognitive; b) affective; c) behavioural [3].

Cognitive reactions are the aesthetic impression ("How beautiful the object is"), the identification of the product's functionality and the association of a product with a certain meaning ("Is it of quality?", "Is it luxurious?", "Does it suit me?"). Affective reactions are: admiration, rejection, amusement, disgust, melancholy, etc. Mainly, there are two human

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behavioural reactions to a product: approach and avoidance. The former indicates interest and can be completed by purchasing the product. The latter represents the failure of the designer, manufacturer, and marketer to attract the interest of the potential buyer.
The process of decoding and understanding the message is influenced by "specific noises": perceptual disorders ("colour-blindness", myopia, deafness, etc.), a background similar to the dominant colour of the product and the observation time of the product (sometimes too short to notice all details).

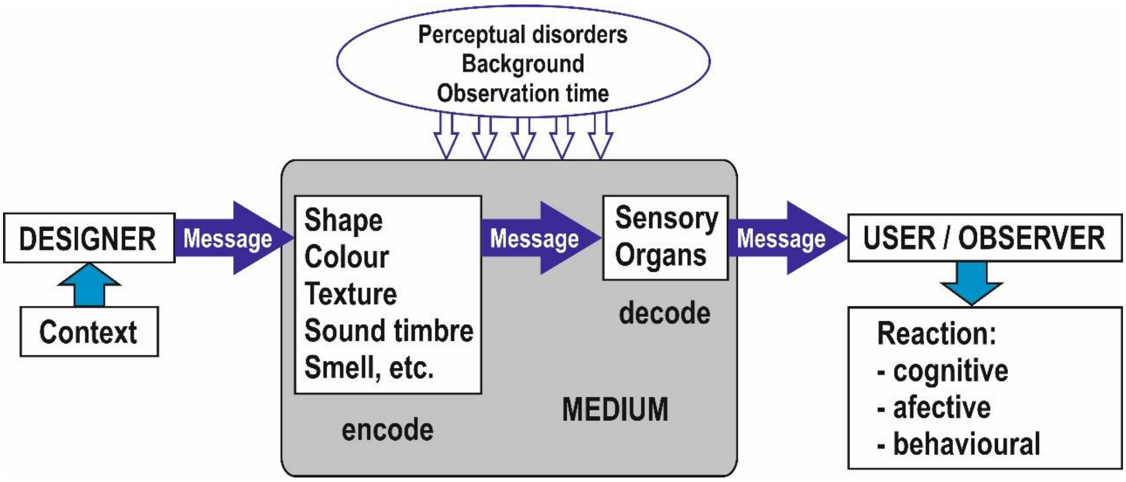

Figure 2. Communication Theory in Industrial Design Field [3]

A simplified example of the application of communication theory in industrial design field is shown in Figure 3. The designer receives an order from a manufacturer specifying that the product should look elegant but have a cheerful note. Added to this is the designer's belief that products should have a professional look. Then, the designer encodes the meaning in aesthetic elements: elegance is conferred by the colour black, cheerfulness by the orange colour, and professionalism by the prismatic appearance (straight edges and right corners).

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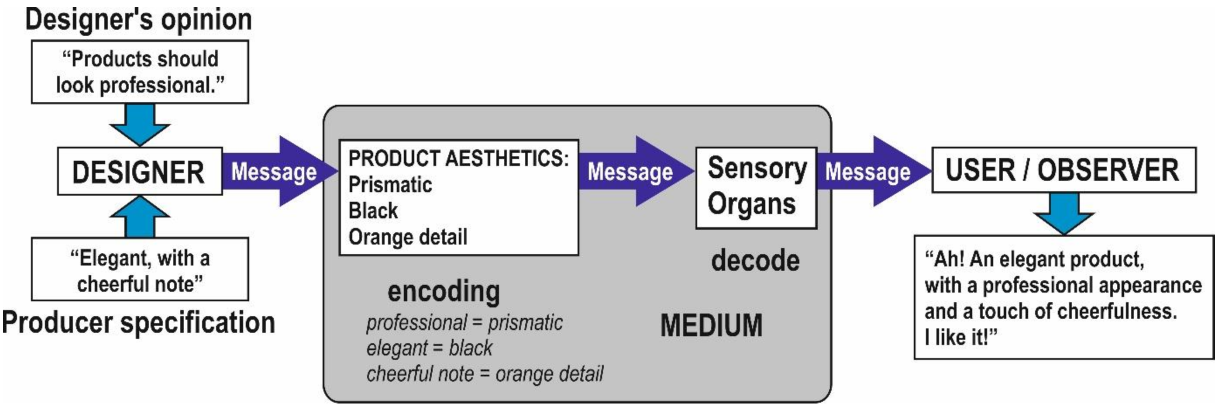

Figure 3. Communication Theory in Industrial Design (example)

2. *Technological Conditioning of Industrial Design*

A product (and more precisely its parts) is made of different materials using different technologies. Each material can be processed by several technologies, but not by absolutely any technology. Technologies and associated materials are chosen according to their contribution to the following goals: a) obtaining the designed shape; b) reaching the prescribed precision parameters; c) ensuring the functional parameters (resistance, hardness, etc.); d) obtaining an aesthetic in line with the values and requirements of the market segment.

As mentioned above, not all materials are processed by all technological processes. Here are some examples: Natural wood cannot be processed by electro erosion, and ordinary ceramics cannot be manufactured by cutting. Moreover, each processing method requires certain characteristics of the shape to ensure that the processing will take place efficiently. In some cases, non-compliance with these imposed requirements leads to the impossibility of processing the part using the respective process. Due to the existence of this shape-material-process correlation, technology professionals easily identify the processing method by which a part was made. The shape-material-procedure correlation has been materialized into the scientific concept of manufacturability.

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Manufacturability is the set of formal characteristics of a part, made of a specified material, which indicates the ease or difficulty of its manufacture through a certain technological process.

For example, parts made of plastic materials that are obtained by mould injection should have slightly inclined vertical walls in order to be easily removed from the mould. The value of the inclination angle varies between 30' and 3°. The inclination angle is a manufacturability characteristic.

Unlike mould injection, additive technologies have fewer manufacturability conditions imposed on the shape of the parts and allow obtaining much more varied shapes. But there are still technological limitations: the maximum size of the part depends on the plates of the 3D printer, high processing time, lower and variable strength in the part body, average dimensional accuracy, etc.

In any case, the industrial designer should document herself/himself on the manufacturability associated with the processing technology and material of the part, especially when designing for the first time with that material.

3. Industrial Design and the Human Being

There is a tendency to reduce the complex relationship between the human being and the product only to the relationship between the user and the object of her/his activity. It is obviously a wrong approach in its simplification. Considering the complexity of the relationship between human being and product, it can be appreciated that the human being can be placed in one of the following postures: creator (designer of the product at level of specifications and drawings); producer (manufacturer of the product); buyer; owner; user; and observer.

From the perspective of this work, the focus is on the buyer posture. The buyer is the person who decides, based on objective and subjective criteria, to purchase a product. The buyer purchases the product for her/his own use, to be used by others or to offer it as a gift.

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The factors that influence consumer behaviour are [4]: a) cultural; b) social (group, family, social role, and status); c) personal (age and life cycle stage, occupation, income, lifestyle, and personality); d) psychological (motivation, perception, learning, beliefs, and attitudes). But any marketing or sales specialist can easily operate with these factors, so it is not necessary to focus on these details.

Considering product aesthetics, a complex characteristic that combines a person's interest and competence in industrial design field becomes important. This complex feature was introduced by Bloch et al. [5], who named it Centrality of Visual Product Aesthetics (CVPA), and which indicates "the level of significance that visual aesthetics hold for a particular consumer in her/his relationship with products". By applying this concept and the associated methodology, one can identify people with high level of CVPA and those with low level of CVPA. Obviously, people with high CVPA are the ones who are interested in purchasing a product with a remarkable design (high level of product aesthetics). Apart from the fact that these people have an innate inclination for beautiful objects, they have also acquired (formally, but especially informally) considerable knowledge in product aesthetics [6].

It thus becomes important for the industrial designer and product manager to determine the CVPA level for the market segment they target. Centrality of Visual Product Aesthetics (CVPA) can be estimated with the help of the following construct [6], using Likert scales:

Aesthetic Pleasure and Loyalty

I enjoy seeing displays of products that have superior designs.

A product design is a source of pleasure for me.

I am proud of my product brands.

Response

Sometimes the way a product looks seems to reach out and grab me.

When I see a product that has a really great design, I feel a strong urge to buy it.

I like to think that the products that belong to me express my identity.

I love products that have the same personality as mine.

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Acumen

Being able to see subtle differences in product designs is one skill that I have developed over time.

I see things in a product design that other people tend to pass over.

I have the ability to imagine how a product will fit in with designs of other things I already own.

Product Involvement

I like to find out how a certain product is made.

I like to make detailed comparisons between products of the same kind.

I read carefully the articles written by experts about the products that interest me.

Price Indifference

I am not interested in the products that have the lowest price in their category.

The low price of a product probably hides major quality deficiencies.

4. *Design Methods for Product Aesthetics*

Conceiving the product aesthetics must always start from the needs and desires of the consumer and more precisely from the needs and desires of the market segment targeted through the launch of the new product.

Necessity (need) is the humans' and other living beings' state determined by the lack of an object, phenomenon or relationships indispensable for survival, fulfilment of social functions, or achievement of a satisfaction state.

Desire is the state of mind of an individual who tends to possess a certain object or to have a certain relationship with other beings.

As mentioned in the definition, necessity is associated with the "functioning" of man as a biological being and as a social being. Desire is related to the imaginary self-projection of man in an ideal situation. Human desires are generated by culture, advertising, and the perceived image of oneself.

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Designing the product aesthetics is an integral part of the product design process and starts from the very conceptual design stage. A quality product cannot be made, if the aesthetics design is not carried out simultaneously and in correlation with the design of the other aspects of the product: mechanical, electrical, electronic, etc.

Designing product aesthetics does not mean the application of a single method and above all it does not mean the rigid performance of stages and phases “by numbers”. Designing product aesthetics is not at all like designing a gearbox.

Another aspect that differentiates the design of product aesthetics from the technical design is the relationship with innovation. If the maximum use of innovation is aimed at in technical design, in the design of product aesthetics innovation should be introduced sparingly, because the public is quite conservative and needs to discover familiar visual elements to which it can relate. Thus appeared the recommendation expressed suggestively by the famous designer Raymond Loewy [7]: "Most advanced, yet acceptable" [by market].

It can be considered that the methods and techniques used in the complex process of generating product aesthetics fall into four broad categories:

- documentation methods;
- creativity methods;
- auxiliary design methods;
- actual design methods.

*4.1. **Documentation Methods***

The industrial designer (individual or within the design team) receives a set of information to guide her/him in the process of designing the product aesthetics. This set of information has various names in specialized literature or within companies: brief, theme-programme, etc. Starting from the information included in the initial set (which is always incomplete), the industrial designer must document herself/himself in order to create a complete information system based on which to design the product aesthetics.

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In order to perform the documentation phase, the designer has at her/his disposal a series of methods and techniques:

- competition analysis (using tables or multidimensional scaling);
- historical research;
- questionnaire;
- interview;
- focus group;
- observing the product in use;
- empathy diagram;
- sentence completion test.

Among the methods and techniques listed above, historical research is quite important for product aesthetics.

The ***historical research*** is carried out (in the minimal case) by making a small catalogue with significant products of the respective class, chronologically ordered. To deepen the research, information about the material, technology, etc. can be added to the product images. There can also be highlighted the products with great success on the market, as well as those which, although innovative from a technological or aesthetic perspective, were more or less significant failures.

Historical research helps the industrial designer to better understand the product and its aesthetic aspects. Historical research can indicate, when carried out thoroughly, the general direction of evolution of the respective class of products. The method can be a basis for understanding the philosophies, cultural implications, and emotional qualities of previous products.

The results of the historical research represent material for discussion between the industrial designer and colleagues or between the industrial designer and the other members of the design team. Later, these results can constitute a reference point in the concept evaluation.

If the targeted market segment possesses knowledge of aesthetics (high level of CVPA), the industrial designer can play with the historical formal elements to give the observers the intellectual satisfaction of discovering them.

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4.2. *Creativity Methods*

Creativity methods have been in the attention of specialists and general public since at least the middle of the last century. Creativity methods were invented by many researchers, and the ones that became classic were derived in several variants. Since the vast majority of professionals have applied a creativity method at least once, it is recommended that everyone should apply the method she/he is used to and only when the method proves ineffective, she/he should try another one.

Here is a short list of creativity methods:

- brainstorming;
- synectics;
- six thinking hats;
- lateral thinking process.

Since a very large number of ideas are generated following the application of a creativity method, it is recommended that new ideas should be classified in the following categories:

- useful ideas, directly applicable;
- useful ideas, but not for the organization;
- useful ideas, but not for that moment;
- ideas that still need to be processed;
- interesting, but impractical ideas;
- worthless ideas;
- impossible ideas.

4.3. *Auxiliary Design Methods*

Auxiliary design methods do not allow obtaining any directly applicable result in the design process, but they considerably facilitate this process. These methods and techniques allow the deepening of knowledge about the product, aesthetics, typical consumer, etc. and stimulates the industrial designer's imagination.

Auxiliary design methods and techniques that can be used by industrial designers are:

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- character profiling;
- scenario method;
- mind map;
- 9 windows technique;
- cultural matrix;
- mood board.

A representative technique for auxiliary design methods is the ***Mood Board***. A Mood Board is basically a cardboard on which are pasted images that visually incorporate the idea or the concept of a product, service, or corporate identity. Mood Board is a collage of visual elements that involve a good mood for the creator or the person who benefits from the result of the design process. The Mood Board does not have a standardized format. A model to follow in creating a Mood Board is presented in the Figure 4.

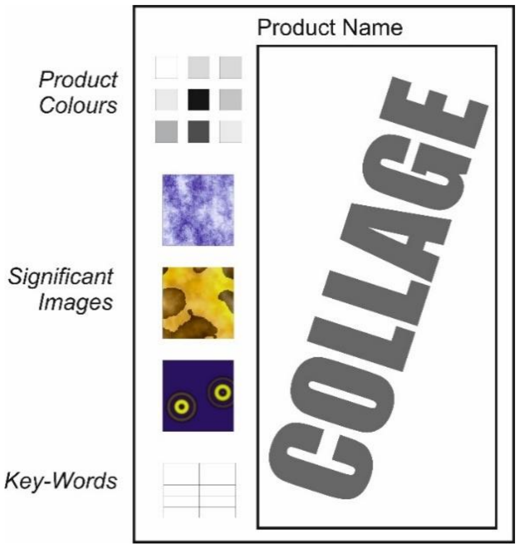

Figure 4. Mood Board (model) [3]

Pasted images can be:

- actual images of favourite products, beloved beings, treasured places, etc.;
- colour samples;
- words (word, font, font size, colour);

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- two-dimensional fragments of packaging (wrapping paper, fragments of plastic or paper bags, etc.);
- (roughly) two-dimensional fragments of objects.

Image sources are:

- magazines;
- books;
- catalogues;
- digital images.

Of course, the Mood Board can also be created in a digital version, but it is not as effective, because the three-dimensionality, the shine, and the different texture of the different materials, etc. are lost.

4.4. Actual Design Methods

In popular culture, designing product aesthetics means a sublime moment of inspiration enjoyed by the talented designer. Perhaps such an approach can give acceptable results in the case of very simple products, with a minimal shape and consisting of a single piece. In the case of complex products, such an approach has no chance of success.

Based on the information contained in the specialized literature, a methodology can be sketched that, at the same time, presents a high degree of generality and covers the entire design process. Such a methodology for designing the product aesthetics would include the following steps:

- defining and clarifying the design problem;
- identification of consumer needs;
- identifying the technical, economic, and ergonomic functions of the product;
- identifying the other functions of the product;
- evaluation of functional, technological, and economic constraints;
- information and documentation;
- incubation of solutions;
- applying creativity methods;
- generation of multiple new solutions to the design problem;

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- selecting the optimal solution;
- developing and detailing the optimal solution;
- testing the optimal solution;
- production of physical models or prototypes;
- testing physical models or prototypes;
- improving the solution.

It should be emphasized that no specific design method covers the above sketched methodology in its entirety. During the product design and development process, several methods and techniques from different areas should be applied (documentation, creativity, actual design, etc.).

To design the product aesthetics, one or more of the methods and techniques included in the following list can be applied:

- Morphological Chart;
- Shape Grammar;
- Designing Product Semantics;
- Product Metaphor Generation;
- Design for Experience;
- Design for Emotion;
- Designing Product Personality;
- Kansei Design;
- Design Thinking;
- Participatory Design (Co-Design);
- Designing for Behaviour Change.

Designing Product Semantics [8] is an example of a method that can be successfully applied to the design of product aesthetics, taking into account the communication theory in design. The phases of the methodology are described below:

- establishment of the objectives and general restrictions related to product;
- identification of the product context of use;
- generation of a list of attributes required to be associated with the product to fulfil the semantic objective;

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- generation of a list of attributes to be avoided;
- analysis, grouping and ranking of attributes;
- search for concrete solutions that materialize the considered attributes;
- assessment, selection, and semantic integration of feasible solutions;
- assessment of the selected solutions from the point of view of technical-economic restrictions.

Establishment of the objectives and general restrictions related to product consists in determining the semantic character that should be communicated to the market segment to which the product is intended. The semantic character can be indicated by a single word or, preferably, by a complete description. Examples of such words are: elegance, high technology, contemporary, traditional, futuristic, etc.

As part of identification of the product context of use, the following aspects are recorded and analysed: a) the opinions of users and buyers (if the buyer is not the product user); b) trends manifested in the field and c) progress in neighbouring fields.

Next it is the generation of a list of attributes required to be associated with the product in order to fulfil the semantic objective. The use of adjectives is recommended. Here are some examples of desirable attributes for a truck cab: mechanical, full of energy, controlled force, reliable, etc. It should be paid attention to the fact that the attributes refer to the way the product looks and not to the way it works.

Generation of a list of attributes to be avoided prevents the designer from deviating from her/his goal. Logically, avoidable attributes are antagonistic to desirable attributes. It is recommended that avoidable attributes pair with desirable ones. It is exemplified by the expressions: “full of energy, but not brutal” and “sophisticated, but not complex”. The avoidable attributes can also result from the semantic history of the product and from the market analysis.

Sometimes the attributes are too numerous, and their operation becomes difficult. That is why attributes are grouped into families. Thus, for example, “repetitive, interconnected, integrated and interchangeable” are grouped under the name “modulated”. The ranking aims

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to order the attributes according to their contribution to the fulfilment of the semantic objective.

Afterwards, concrete solutions will be sought to materialize the considered attributes. The solutions will be expressed in terms of shape, colour, texture and material. For example, let us consider that the desirable attributes are strong and precise, and those to be avoided are brutal and imprecise. A prismatic shape is recommended, but not with sharp edges. The colours can be black, dark neutral greys or dark metallic shades. The texture will be smooth, even mirror. The material will be metallic.

As a result of the previous stage, it resulted a set of solutions that conform to the attributes. It is time to assess, select and semantically integrate the generated solutions according to the semantic objective and the context of use.

A new assessment phase follows, in which the criteria are the technical-economic restrictions. The solutions that can present an extremely interesting semantic content, but which cannot be applied due to the low technology of the form or because of the too high production costs, will be eliminated.

5. Assessment Methods for Product Aesthetics

Assessment means to establish the value in a systematic manner, based on objective and clear criteria. Usually, the assessment of product aesthetics means the appraisal of the product appearance against a certain list of criteria. Several issues can occur:

- Evaluators are not motivated in performing a correct evaluation.
- Evaluators are reluctant to honestly express their opinion, believing that they will be assessed based on what they express.
- (often) Likert scales are used, and numbers stimulate the left hemisphere of the brain.
- The wrong designation of a positive or negative character for the attributes associated with certain criteria.
- The list of criteria is not well chosen (includes unclear or irrelevant criteria).

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The assessment performed by design critics is welcome for magazine articles and blogs or for award juries. However, if the assessment is made by the manufacturing company to improve the appearance of its own products, it is recommended to involve representatives of the market segment, because they know what they want and, in the end, they will purchase the company's products.

Often, non-professional evaluators are impressed by the organization and environment created for the assessment and censor their opinions, unjustifiably believing that they are in danger of being laughed at if they express some of their opinions honestly. This situation is avoided by using projective methods in which evaluators express the assessment of fictional characters in relation to the product aesthetics.

It is known that product aesthetics is the field of the right hemisphere of the human brain - the artistic hemisphere. But by assigning grades (numbers), the left hemisphere is activated, the one that cannot correctly evaluate product aesthetics. That is why it is recommended to use attributes and not numbers.

There are absolutely no positive and absolutely no negative aesthetic attributes. For example, a product is appraised using proportion criterion, with the indication that "proportionate" means a ratio close to the golden section (1.618). If a static product has a ratio of, say, 2.5 (disproportioned) with a large horizontal dimension, this does not mean that "disproportioned" is a negative attribute. Therefore, it is recommended that the attributes be set as positive or negative depending on their contribution to the fulfilment of the product purpose and to the materialisation of the values of the considered market segment.

Wishing to be outstanding, certain authors in the product aesthetics field launch new assessment criteria. An example of such a criterion is “tectonics”. Let us imagine that somebody is assessing the tectonics of a car... It is obvious that this criterion is unclear. The specialized literature includes numerous criteria systems. Without being the only effective system of criteria, it can be used the following system, which resulted from a research carried out with the involvement of consumers [9]:

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- functionality;
- ergonomics;
- harmony;
- balance;
- proportion;
- compactness;
- elegance;
- complexity;
- neatness;
- novelty ratio;
- originality;
- distinctiveness.

6. *Conclusions*

The product aesthetics has lately become important following the evolution of the global market. Industrial design is used, along with the brand, by consumers to make the purchase decision. Product aesthetics is not equally important for all product classes, and the product manager should determine the importance of industrial design for her/his product to know how much to invest in product aesthetics.

Since assigning a meaning to the product is a difficult process, communication theory is applied in product aesthetics. The product becomes the medium of communication, and the aesthetic elements (shapes, colours, textures, smells, etc.) are the codes that carry the message from the industrial designer and manufacturing company to the user and observer.

Technology is conditioning product aesthetics by the fact that each material can only be processed through a limited number of technological processes, and each process has a series of constraints that limit the industrial designer in her/his activity.

In relation to industrial design, man can be placed in different postures. The posture of the consumer is important to study because each market segment has its own characteristics,

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including interest and competence in industrial design (Centrality of Visual Product Aesthetics).

Conceiving the product aesthetics is a complex process which requires the application of different design methods from different fields (documentation, creativity, support and actual design).

Assessing product aesthetics should be carried out in a systematic manner using objective and clear criteria. There should be avoided issues related to evaluators' motivation and self-censorship, excessive use of numbers, preconceptions regarding what is a positive/negative attribute and quality of applied criteria.

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1.2. Additive Manufacturing - Fabrication

Contents

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1.2. Additive Manufacturing – Fabrication

1.2.1.The principle of Additive Manufacturing technologies

A variety of processes, equipment, and materials are used in the production of a three-dimensional object via additive manufacturing. 3D printing is also known as additive manufacturing, because the numerous available 3D printing process tend to be additive in nature, with a few key differences in the technologies and the materials used in this process.
Some of the different types of physical transformations which are used in 3D printing include melt extrusion, light polymerization, continuous liquid interface production and sintering.
Additive Manufacturing technologies of prototypes (Additive Manufacturing - AM) differ fundamentally from material removal processing technologies (chipping, electroerosion, laser processing) and material redistribution processing technologies (casting, injection, forging, molding), because the parts are obtained by adding as much material as and where needed. [1] These technologies emerged as a result of achievements and advances made in fine mechanics, numerical control, laser technology, computers, computer programs, and grace of new innovative materials. [1-124]
These new manufacturing technologies have started to grow in importance, as well as other products for manufacturers, reducing the time from conception to market, and the costs for assimilating and manufacturing new ones. The specificity of these additive manufacturing processes is their ability to make complex three-dimensional parts and objects, starting from a CAD file, without the need for the use of machine tools or certain devices. [1] The basic element of additive prototyping technologies is the "section". Parts are quantified into sections and made using a repetitive, section-by-section construction process, reducing a three-dimensional problem to a plan. This dimensional reduction leads to a decrease in the precision and quality of the surfaces of scale effects. Making a part using AM technology requires the following steps:

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-realization of the three-dimensional (3D) model of the part, using a computer-aided design (CAD) program;
-transferring the CAD model to the sectioning processor. The most well-known method of sectioning is the approximation of the model with planar triangular elements.
-sectioning the 3D virtual model with planes parallel to the working plane of the rapid prototyping machine and generating orders for the machine's control equipment;
-the actual construction of the part (material, the way to use the material, the supports needed during the construction of the model, the gluing to the previous layer, how a new layer will be added, the marking of the contours for each section, the marking of the area between the outer and inner contour of of a section;
-cleaning and finishing the part (operations in which the supports used in the construction and the excess material are removed).
Additive Manufacturing processes were initially used for the production of prototypes, i.e. in the case of small, unique series production. Soon, however, these Additive Manufacturing processes will directly produce functional parts with high precision and very short manufacturing time, whether metal or from other materials, successfully replacing conventional manufacturing technologies that use expensive machine tools. [1,2] Looking at CAD solid modeling, Additive Manufacturing systems are becoming an important motivating factor for companies that produce solid modeling systems, such as Unigraphics, I-DEAS, Catia, AutoCAD, Pro/Engineer, etc. The models obtained through Additive Manufacturing optimize the design of a new model or the modernization of an existing one, these models allow the physical visualization of the product and improve the communication between the manufacturer and the beneficiary. The models manufactured by these new technologies can be used for various testing modes, of which the most implemented are:
- functional tests;

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- simulation tests;
- control tests;
- manufacturing tests;
- fixing and assembly tests;
- packaging tests.

Testing a product manufactured by Additive Manufacturing technologies depends on three factors material, size and design. The tests carried out must lead to a visual acceptance, an understanding of the construction, the functionality of the product and the finalization of the dimensioning elements. Additive Manufacturing technologies have and will have an important role in many industrial fields, from the field of manufacturing to medicine, aerospace, architecture, automotive, electronics, tooling thus giving the technology a strategic importance for the companies that use these technologies. [1]

Laser Additive Manufacturing is a set of innovative, state-of-the-art technologies that have developed explosively in the last two decades. ALM technologies have begun to be used on an increasingly large scale in industry, especially aerospace, automotive and mold making, respectively in the medical field. Laser Additive Manufacturing technologies provide designers with physical replicas of virtual models built in CAD systems. Almost all CAD systems can produce very faithful images of an object, but a physical model will provide more information about the same object (eg design errors) and is easier to understand. The chapter book presented Laser Additive Manufacturing technologies, specific manufacturing equipment and parameters of ALM manufacturing regimes. The development of SLS, DMLS, SLM, EBM, Laser Design/DMD technologies have made and are making possible customized implants from various biocompatible materials.

1.2.2. Types of Additive Manufacturing technologies

Construction of a model with contemporary methods can take anywhere from several hours to several days, depending on the method used and the size and complexity of the

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model. Additive systems can typically reduce this time to a few hours, although it varies widely depending on the type of machine used and the size and number of models being produced simultaneously.

Finishing

Though the printer-produced resolution and surface finish are sufficient for some applications, post-processing and finishing methods allow for benefits such as greater dimensional accuracy, smoother surfaces, and other modifications such as coloration.

The surface finish of a 3D printed part can improved using subtractive methods such as sanding and bead blasting. When smoothing parts that require dimensional accuracy, it is important to take into account the volume of the material being removed.

Some printable polymers, such as acrylonitrile butadiene styrene (ABS), allow the surface finish to be smoothed and improved using chemical vapor processes based on acetone or similar solvents.

Some additive manufacturing techniques can benefit from annealing as a post-processing step. Annealing a 3D-printed part allows for better internal layer bonding due to recrystallization of the part. It allows for an increase in mechanical properties, some of which are fracture toughness, flexural strength, impact resistance, and heat resistance. Annealing a component may not be suitable for applications where dimensional accuracy is required, as it can introduce warpage or shrinkage due to heating and cooling.

Additive or subtractive hybrid manufacturing (ASHM) is a method that involves producing a 3D printed part and using machining (subtractive manufacturing) to remove material. Machining operations can be completed after each layer, or after the entire 3D print has been completed depending on the application requirements. These hybrid methods allow for 3D-printed parts to achieve better surface finishes and dimensional accuracy.

The layered structure of traditional additive manufacturing processes leads to a stair-stepping effect on part-surfaces that are curved or tilted with respect to the building platform. The effect strongly depends on the layer height used, as well as the orientation of a part

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surface inside the building process. This effect can be minimized using "variable layer heights" or "adaptive layer heights". These methods decrease the layer height in places where higher quality is needed.

Painting a 3D-printed part offers a range of finishes and appearances that may not be achievable through most 3D printing techniques. The process typically involves several steps, such as surface preparation, priming, and painting. These steps help prepare the surface of the part and ensuring the paint adheres properly.

Some additive manufacturing techniques are capable of using multiple materials simultaneously. These techniques are able to print in multiple colors and color combinations simultaneously and can produce parts that may not necessarily require painting.

Some printing techniques require internal supports to be built to support overhanging features during construction. These supports must be mechanically removed or dissolved if using a water-soluble support material such as PVA after completing a print.

Some commercial metal 3D printers involve cutting the metal component off the metal substrate after deposition. A new process for the GMAW 3D printing allows for substrate surface modifications to remove aluminium or steel.

A variety of processes, equipment, and materials are used in the production of a three-dimensional object via additive manufacturing. 3D printing is also known as additive manufacturing, because the numerous available 3D printing process tend to be additive in nature, with a few key differences in the technologies and the materials used in this process. Some of the different types of physical transformations which are used in 3D printing include melt extrusion, light polymerization, continuous liquid interface production and sintering.

The standard ISO/ASTM52900-15 defines seven categories of additive manufacturing (AM) processes within its meaning. They are:

- Vat photopolymerization;
- Material jetting;
- Binder jetting;

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- Powder bed fusion;
- Material extrusion;
- Directed energy deposition;
- Sheet lamination.

The main differences between processes are in the way layers are deposited to create parts and in the materials that are used. Each method has its own advantages and drawbacks, which is why some companies offer a choice of powder and polymer for the material used to build the object. Others sometimes use standard, off-the-shelf business paper as the build material to produce a durable prototype. The main considerations in choosing a machine are generally speed, costs of the 3D printer, of the printed prototype, choice and cost of the materials, and color capabilities. Printers that work directly with metals are generally expensive. However, less expensive printers can be used to make a mold, which is then used to make metal parts.

1.2.3. Processes and printers

The variety of processes and equipment allows for numerous uses by amateurs and professionals alike. Some lend themselves better toward industry use (in this case the term Additive Manufacturing is preferred) whereas others make 3D printing accessible to the average consumer. Some printers are large enough to fabricate buildings whilst others tend to micro and nanoscale sized objects and in general many different technologies can be exploited to physically produce the designed objects.

Several 3D printing processes have been invented since the late 1970s. The printers were originally large, expensive, and highly limited in what they could produce.

A large number of additive processes are now available. The main differences between processes are in the way layers are deposited to create parts and in the materials that are used. Some methods melt or soften the material to produce the layers, for example. selective laser melting (SLM) or direct metal laser sintering (DMLS), selective laser sintering (SLS), fused

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deposition modeling (FDM), or fused filament fabrication (FFF), while others cure liquid materials using different sophisticated technologies, such as stereolithography (SLA).

Table 1. Additive Manufacturing technologies and materials

Type	Technologies	Materials
Material jetting	**Drop-on-demand or continuous (single- or multi-nozzle) particle deposition**	**Hot-melt materials (wax, thermoplastic, metal alloy), dispersed materials (technical ceramics, metals, polymers)**
Material extrusion	**Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) and fused pellet fabrication or fused particle fabrication**	**Thermoplastics, eutectic metals, edible materials, rubbers, modelung clay, plasticine**
	Robocasting or MIG wlding 3D printing or Direct Ink Writing (DIW) or extrusion based additive manufacturing of metals (EAM) and ceramics (EAC)	**Metal-binder mixtures such as metal clay, ceramic-binder mixtures (including ceramic clay and ceramic slurries), cermet, metal matrix composite, ceramic matrix composite, metal (MIG welding)**
	Additive Friction Stir Deposition (AFSD)	**Metal alloys**
	Composite Filament Fabrication (CFF)	**Nylon or nylon reinforced with carbon, Kevlar or glass fibers**
Light polymerized	**Stereolithography (SLA)**	**Photopolymer (including preceramic polymers)**
	Digital Light Processing (DLP)	**Photopolymer**
	Continuous liquid interface production (CLIP)	**Photopolymer + thermally activated chemistry**
Powder Bed	**Powder bed and inkjet head 3D printing (3DP)**	**Almost any metal alloy, powdered polymers, paster**
	Electron Beam Melting (EBM)	**Almost any metal alloy including titanium alloys**
	Selective Laser Melting (SLM)	**Titanium alloys, Co-Cr alloys, Stainless steels, aluminium**
	Selective Laser Sintering (SLS)	**Thermoplastics, metal powders, ceramic powders**
	Selective Heat Sintering (SHS)	**Thermoplastic powders**
	Direct Metal Laser Sintering (DMLS)	**Metal alloys**
Laminated	**Laminated object manufacturing (LOM)**	**Paper, metal foil, plastic film**
	Stratoconception	
Powder fed	**Laser Metal Deposition (LMD) or Directed Energy Deposition (DED)**	**Metal alloys**
	Extreme High-speed Laser Cladding (EHLA)	**Metal alloys**
Wire	**Electron Beam Freeform Fabrication (EBF3)**	**Metal alloys**
	Wire-arc additive manufacturing (WAAM)	**Metal alloys**
Freezing	**Rapid Freeze Prototyping (RFP)**	**Water**
3D Bioprinting	**3D Bioprinting**	**STEM cells, biopolimers**

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In case of Laminated Object Manufacturing (LOM), thin layers are cut to shape and joined (e.g., paper, polymer, metal). Particle deposition using inkjet technology prints layers of material in the form of individual drops. Each drop of solid ink from hot-melt material actually prints one particle or one object. Color hot-melt inks print individual drops of CMYK on top of each other to produce a single color object with 1-3 layers melted together. Complex 3D models are printed with many overlapping drops fused together into layers as defined by the sliced CAD file. Inkjet technology allows 3D models to be solid or open cell structures as defined by the 3D printer inkjet print configuration. Each method has its own advantages and drawbacks, which is why some companies offer a choice of powder and polymer for the material used to build the object. Others sometimes use standard, off-the-shelf business paper as the build material to produce a durable prototype. The main considerations in choosing a machine are generally speed, costs of the 3D printer, of the printed prototype, choice and cost of the materials, and color capabilities.

Printers that work directly with metals are generally expensive. However less expensive printers can be used to make a mold, which is then used to make metal parts.

1.2.4. Fused Deposition Modeling (FDM)

FDM (Fused Deposition Modeling), in translation Thermoplastic Extrusion Modeling was patented by Stratasys Inc in 1993. [1,18]

Thermoplastic extrusion/melt deposition modeling is the most used additive manufacturing technology due to its simplicity and affordability. It is used in modeling, prototyping but also in production applications. Other names used are:

MEM (Melting Extrusion Modeling), TPE (Thermoplastic Extrusion), FFF (Fused Filament Fabrication).

In this process, the material is applied in small droplets through a diameter nozzle

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small, similar to how a common 2D inkjet printer works, but is layered on a platform to build a 3D object and follows processing through photopolymer solidification using UV rays. [1,18]
The FDM manufacturing process uses two materials: model material and support material. The three-dimensional geometric model in .stl format is taken in the QuickSlice program and processed to obtain the machine control program (SML-Stratasys Modeling Language command file). Principle scheme of the FDM process is shown in figure 1.

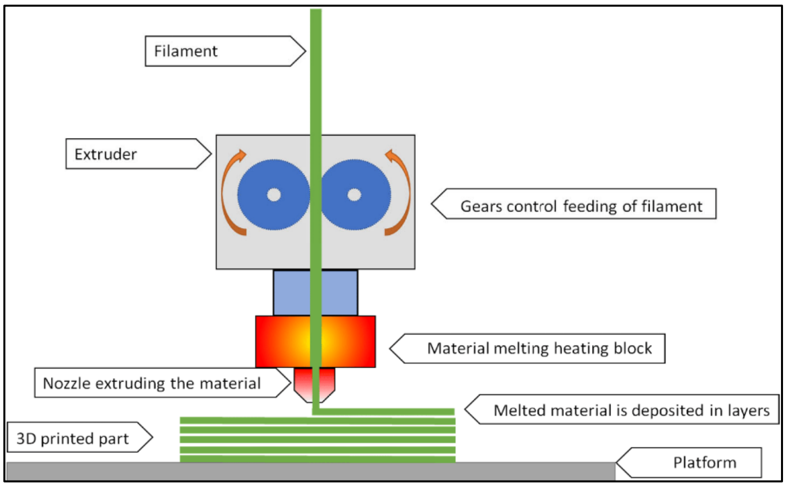

Fig.1. Fused Deposition Modeling (FDM) principle [19]

The Magna Drive manufacturing system has two deposition heads (one for support material, other for part material) that can move independently and has a high-performance system of order to move the deposition heads. This system is very reliable, fast and accurate.
Filament is fed from a large spool through a moving, heated printer extruder head, and is deposited on the growing work. The print head is moved under computer control to define the printed shape. Usually the head moves in two dimensions to deposit one horizontal plane, or layer, at a time; the work or the print head is then moved vertically by a small amount to begin a new layer. The speed of the extruder head may also be controlled to stop and start

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deposition and form an interrupted plane without stringing or dribbling between sections. "Fused filament fabrication" was coined by the members of the RepRap project to give an acronym (FFF) that would be legally unconstrained in its use.

Fig.2. Assembly of parts obtained by the FDM process [20]

Fused filament printing is now the most popular process (by number of machines) for hobbyist-grade 3D printing. Other techniques such as photopolymerisation and powder sintering may offer better results, but they are much more costly. The 3D printer head or 3D printer extruder is a part in material extrusion additive manufacturing responsible for raw material melting or softening and forming it into a continuous profile. A wide variety of filament materials are extruded, including thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyethylene terephthalate glycol (PETG), polyethylene terephthalate (PET), high-impact polystyrene (HIPS), thermoplastic polyurethane (TPU) and aliphatic polyamides (nylon).The advantages of FDM technology consist of very office-

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friendly technology, quiet and safe. Usable objects and parts can be produced, the palette of materials being quite wide. The price of 3D printers (kits and assembled models) as well as consumables (rolls with plastic filaments) is extremely affordable. [1,18,19] The disadvantages of this process are the slow construction speed in the complex geometries case, the possibility of non-uniformly printed areas (layers unglued), low impermeability, poor resolution and accuracy for small parts and details fine (microns). Disadvantages for kits and 3D printers is the long assembly and calibration time (kits), print quality is variable, high scrap rate (in the beginning), very fast small construction for complex parts, parts limited in size due to deformations in printing, unevenly printed areas (unglued layers). The processing precision is of the order of tens of millimeters and is influenced by the precision of the .stl model and the choice of technological processing parameters. [1,18,19] Applications of the FDM process consist in the production of parts and subassemblies, resistant for functional testing, conceptual design as in fig.2, presentation of models and marketing, detail parts for industrial or medical applications, subassemblies from plastic for high temperature applications, very small series productions. Casting forms, matrix prototyping (structural skeletons) can be made for tissue engineering medical applications, rapid prototyping of small parts and tools size.

1.2.5. Laminated object manufacturing (LOM)

Laminated object manufacturing (LOM) is a rapid prototyping system developed by Helisys Inc. (Cubic Technologies is now the successor organization of Helisys) In it, layers of adhesive-coated paper, plastic, or metal laminates are successively glued together and cut to shape with a knife or laser cutter. Objects printed with this technique may be additionally modified by machining or drilling after printing. Typical layer resolution for this process is defined by the material feedstock and usually ranges in thickness from one to a few sheets of copy paper.

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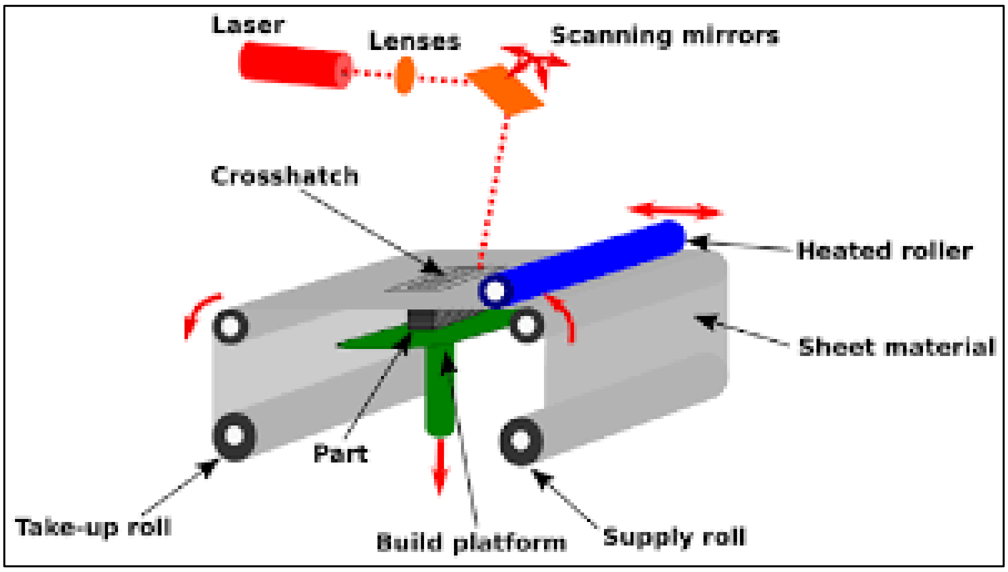

Fig.3. Schema procedeului de fabricaţie LOM [15]

The first stage that must be completed to obtain a part through a process of rapid prototyping is the three-dimensional geometric modeling of the part respectively. The virtual geometric model must then be converted from the native format of modeling program, in a file format supported by the control program of rapid prototyping system. The file format most used for this purpose is the STL (Stereo Lithography) format. In essence, an STL representation is an approximation of the geometric model through a collection of triangular facets. [1.15]

In figure 3, the scheme of the LOM manufacturing process is represented. The virtual geometric model, in .stl format, is taken over by the command program al
machine (LOM Slice) and processed in order to make the physical part. It is sectioned with planes parallel to the working plane of the machine (XOY) in order to obtain the profile of the part at certain Z elevation.

Based on the geometric information obtained from the sectioning of the virtual model and the technological data entered by the operator, the cutting device formed from a laser beam control system, materializes the section. Excess material it is cut by the laser beam, in the form

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of a hatch with the hatching directions parallel to the axes X and Y. After the upper layer is fully processed, the platform is retracted (on Z axis), the material advances one step, the platform rises to bring the new layer of material in the focus plane of the laser beam (working plane of the machine), a heating roller and pressing glues the "n" layer to the "n-1" layer and then the process of materializing the section by cutting. [1.16]

The manufacturing process is repetitive and is completed at the moment when the last one virtual section was physically materialized. The sectioning step along the Z axis is given by the thickness of the material used in the manufacture of the part. The most commonly used material is LOM paper, special paper that has an adhesive layer on one side. The processed paper parts have characteristics and physical appearance similar to the parts made of wood, as in Figure 4. [1.16]

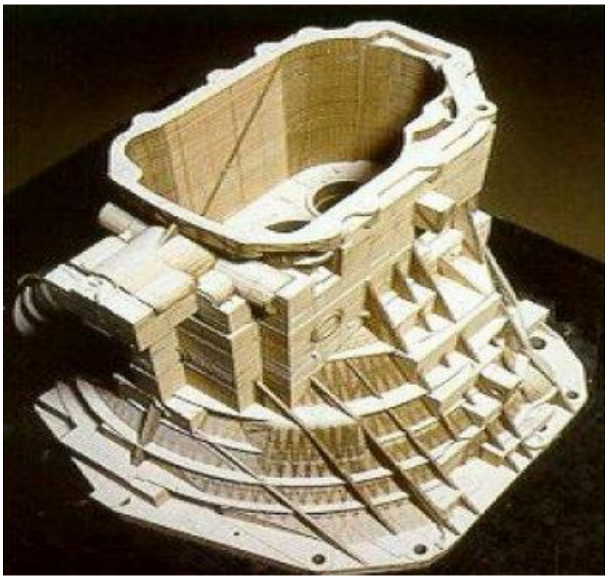

Fig.4. Part manufactured by LOM [17]

Other types of materials can also be used, such as: plastic materials, metallic materials, composite materials and ceramic materials.

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The process is performed as follows:

1. Sheet is adhered to a substrate with a heated roller.
2. Laser traces desired dimensions of prototype.
3. Laser cross hatches non-part area to facilitate waste removal.
4. Platform with completed layer moves down out of the way.
5. Fresh sheet of material is rolled into position.
6. Platform downs into new position to receive next layer.
7. The process is repeated until full model or prototype prepared.

After the last layer has been processed, post-processing takes place, which includes all the operations that are done in order to separate the piece from the excess material, as well as finishing operations.

LOM technology allows the layered manufacturing of the 3D object from layers of paper or plastic that are glued together, one on top of the other and cut with a knife or other a laser. The printing material used can be supplied both in the roll (plastic) and in sheets or sheets (paper).

Initially, the 3D CAD model is converted into cross-sections (slices) of the object and then sent to the printer.

With the help of a laser source or a knife, the printer cuts from the sheet of material solid the layers that will make up the 3D piece.

The rest of the material not used after cutting is finely checkered by the knife (or the source laser) so that at the end of the process it can be removed manually. The finished layer is glued to the previous layer using an adhesive applied to the underside of the sheet.

The cost of equipment using this technology is quite expensive, however they have the great advantage of using extremely cheap consumables (ordinary paper).

The average precision of the processing of LOM parts is of the order of tens of millimeters. In the during lamination, the layers of material neither stretch nor contract, so they do not want introduces stresses that lead to deformation of the model.

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In the case of the LOM process, it is not necessary to build supports to sustain the part during construction, as the excess material in each layer constitutes support for the next layer.

The advantages of LOM technology lie in very cheap printing materials (paper regular A4), good accuracy and precision, allows printing larger models which do not have complicated details. 3D prototypes printed in full color allow a great visual impact. The equipment used for printing does not use powders, chemicals or hazardous post-processing operations. [1.16]

The disadvantages of LOM technology are the limited range of materials, poor mechanical properties of materials, unused material must be removed by hand, material waste quite large and limited print volumes.

Applications of LOM technology are in the field of prototypes, models of architecture, aerospace, mechanical domain. 3D models manufactured by the LOM process are bulky, not highly detailed and require a cheap manufacturing cost.

Color printing has applicability in many areas as: architecture, conceptual design, marketing models, scientific visualization, education.

1.2.6. Stereolithography (SLA)

Stereolithography (SLA or SL) is an additive manufacturing technology known as a manufacturing process by solidifying the raw material in a liquid state due to photopolymerization. Stereolithography was the first process that allowed the generation of a model physically, using model data, directly from the computer. [1.21]

Stereolithography (Fig.5) is an additive manufacturing process that, in its most common form, works by focusing an ultraviolet (UV) laser on to a vat of photopolymer resin. With the help of computer aided manufacturing or computer-aided design (CAM/CAD) software, the UV laser is used to draw a pre-programmed design or shape on to the surface of the photopolymer vat. Photopolymers are sensitive to ultraviolet light, so the resin is photochemically solidified and forms a single layer of the desired 3D object. Then, the build platform lowers one layer and a

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blade recoats the top of the tank with resin. This process is repeated for each layer of the design until the 3D object is complete. Completed parts must be washed with a solvent to clean wet resin from their surfaces.

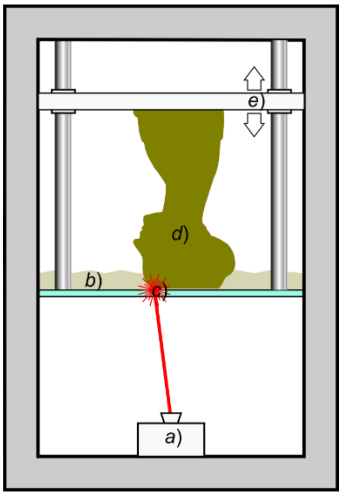

Fig.5. Stereolithography (SLA) principle [124]

It is also possible to print objects "bottom up" by using a vat with a transparent bottom and focusing the UV or deep-blue polymerization laser upward through the bottom of the vat. An inverted stereolithography machine starts a print by lowering the build platform to touch the bottom of the resin-filled vat, then moving upward the height of one layer. The UV laser then writes the bottom-most layer of the desired part through the transparent vat bottom. Then the vat is "rocked", flexing and peeling the bottom of the vat away from the hardened photopolymer; the hardened material detaches from the bottom of the vat and stays attached to the rising build platform, and new liquid photopolymer flows in from the edges of the partially built part. The UV laser then writes the second-from-bottom layer and repeats the process. An advantage of this bottom-up mode is that the build volume can be much bigger than the vat itself, and only enough photopolymer is needed to keep the bottom of the build

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vat continuously full of photopolymer. This approach is typical of desktop SLA printers, while the right-side-up approach is more common in industrial systems.

This technology allows the creation and manufacture of models, prototypes and layered parts, using for solidification, the process of selective photopolymerization, a process that is activated by a light beam and forms bonds between unsaturated molecules forming chains of polymer, figure 5.

This procedure was conceived in 1982 by Charles Hull, and in 1986 it was patented the Stereolithography process. 3D Systems Inc. use this patent for commercialization since 1986. In 1988, the first one was commercialized stereolithography system SLA-1. In 1989, an improved SLA 250 model was presented, and starting from 1990, more productive models are made for voluminous parts, SLA-500 type.

Fig.6. Part manufactured via SLA

Stereolithography requires the use of supporting structures which attach to the elevator platform to prevent deflection due to gravity, resist lateral pressure from the resin-filled blade, or retain newly created sections during the "vat rocking" of bottom up printing. Supports are typically created automatically during the preparation of CAD models and can

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also be made manually, as in figure 6. In either situation, the supports must be removed manually after printing. In figure 7, were used different colored resins in architectural domain for realize the Kretzulescu Palace, manufactured by SLA.

Fig.7. Resins used in architectural domain (Kretzulescu Palace) manufactured by SLA

Other forms of stereolithography build each layer by LCD masking or using a DLP projector.

The liquid materials used for SLA printing are commonly referred to as "resins" and are thermoset polymers. A wide variety of resins are commercially available and it is also possible to use homemade resins to test different compositions for example. Material properties vary according to formulation configurations: "materials can be soft or hard, heavily filled with secondary materials like glass and ceramic, or imbued with mechanical properties like high heat deflection temperature or impact resistance". It is possible to classify the resins in the following categories:

- Standard resins, for general prototyping
- Engineering resins, for specific mechanical and thermal properties

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- Dental and medical resins, for biocompatibility certifications
- Castable resins, for zero ash-content after burnout
- Biomaterial resins, formulated as aqueous solutions of synthetic polymers like polyethylene glycol, or biological polymers such as gelatin, dextran, or hyaluronic acid.

One of the advantages of stereolithography is its speed; functional parts can be manufactured within a day. The length of time it takes to produce a single part depends upon the complexity of the design and the size. Printing time can last anywhere from hours to more than a day. SLA printed parts (Fig.6), unlike those obtained from FFF/FDM, do not exhibit significant anisotropy and there's no visible layering pattern. The surface quality is, in general, superior. Prototypes and designs made with stereolithography are strong enough to be machined and can also be used to make master patterns for injection molding or various metal casting processes.

Although stereolithography can be used to produce virtually any synthetic design, it is often costly, though the price is coming down. Since 2012, however, public interest in 3D printing has inspired the design of several consumer SLA machines which can cost considerably less. Beginning in 2016, substitution of the SLA and DLP methods using a high resolution, high contrast LCD panel has brought prices down to below US$200. The layers are created in their entirety since the entire layer is displayed on the LCD screen and is exposed using UV LEDs that lie below. Resolutions of .01mm are attainable. Another disadvantage is that the photopolymers are sticky, messy, and need to be handled with care. Newly made parts need to be washed, further cured, and dried. The environmental impact of all these processes requires more study to be understood, but in general SLA technologies have not created any biodegradable or compostable forms of resin, while other 3-D printing methods offer some compostable PLA options. The choice of materials is limited compared to FFF, which can process virtually any thermoplastic.

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1.2.7. Digital Light Processing (DLP)

Developed by Texas Instruments, DLP technology has the chip as its main element DMD (Digital Micromirror Device) – an array of micro-mirrors used for fast space modulation of light. [1, 32]

The DLP process is a form of stereolithography, which is used in the services of rapid prototyping. In DLP projectors, the image is created by microscopically small mirrors laid out in a matrix on a semiconductor chip, known as a digital micromirror device (DMD). These mirrors are so small that DMD pixel pitch may be 5.4 µm or less.

The main difference between DLP and SLA is the use of a light projector that solidifies the resin of a photosensitive polymer, compared to a laser as it uses the process of stereolithography.

A DLP printer (Fig.8) projects the 3D cross-sectional image of the object onto the surface of the resin. The resin exposed to the light source hardens while the platform of built of the machine descends, allowing the deposition of a new layer of fresh resin which to be solidified by light. [1,32,33]

Once the part is completely manufactured, post-processing can be done additional, such as removal of the support material, chemical bath and UV drying.

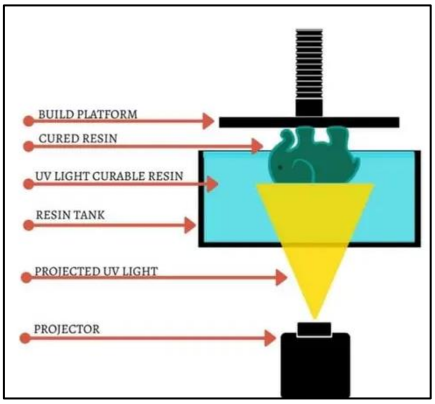

Fig.8. Digital Light Processing (DLP) principle [33]

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The accuracy of the printed parts (Fig.9) is very good. Finishing of printed surfaces is very good. Print speed is good (for multiple objects and complex geometries). The materials used by DLP technology are different types of resins, photopolymers, transparent resins, wax-based polymers.

Fig.9. Parts manufactured by DLP technology

The advantages of DLP technology are fine and precise printed surfaces (use in jewelry industry, dental technology, electronics, architecture, tooling), quite durable prototypes for processing, diverse range of resins including biomedical materials (certificates for use in the medical field) and transparent resins (prototypes in the packaging industry), printers stable with few moving parts. [1,32,33]

The technology enables the prototyping of parts with complex and detailed geometries, great print speed for complex geometries and simultaneous printing of several parts (high productivity). The printed parts can be used as master molds for industries as injection molding, thermoforming and metal casting.

Disadvantages of DLP technology would be more expensive construction materials, price higher printing (for large volumes), requires post-processing operations (UV curing, removal of support material), requires handling of resins.

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1.2.8. Selective Laser Sintering (SLS)

An additive manufacturing layer technology, SLS involves the use of a high power laser (for example, a carbon dioxide laser) to fuse small particles of plastic, metal, ceramic, or glass powders into a mass that has a desired three-dimensional shape.
The laser selectively fuses powdered material by scanning cross-sections generated from a 3-D digital description of the part (for example from a CAD file or scan data) on the surface of a powder bed. After each cross-section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is applied on top, and the process is repeated until the part is completed, as in figure 10.

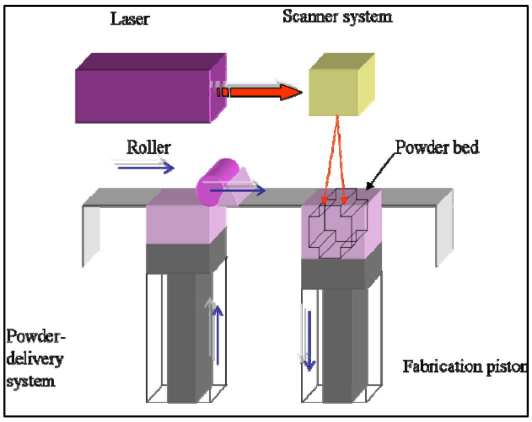

Fig.10. Principle of SLS technology [51]

The SLS selective laser sintering process has been developed and patented over the years 1980 by Dr. Carl Deckard at the University of Texas at Austin. The first equipment of selective laser sintering were commercialized after 1996. [1,37-50]

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Selective Laser Sintering (SLS) processes have been developed after 1992 and is based on design and manufacturing experience gained on stereolithographic equipment (STL) but also on the expansion of technological research on to other groups of materials with mechanical and technological properties closer to the needs of functional assemblies in machine construction (ceramic, ferrous materials and non-ferrous.

Selective laser sintering processes consider a wide variety of materials from which will result in products at a higher level of performance, i.e. with physico-mechanical properties close to the demands in the organs of usual machines.

Rapid prototyping technology helps identify potential problems appear in the design and conception process. With a prototype one can actually see if two surfaces are joining correctly or if the joining points are lining up as they should.

The DTM Sinterstation 2500 (SLS) rapid prototyping system makes prototypes both for beneficiaries in the industrial environment, but also for humanitarian purposes -medical prostheses in case of accidents, especially skulls, as in figure 11.

Because finished part density depends on peak laser power, rather than laser duration, a SLS machine typically uses a pulsed laser. The SLS machine preheats the bulk powder material in the powder bed somewhat below its melting point, to make it easier for the laser to raise the temperature of the selected regions the rest of the way to the melting point.

In contrast with SLA and FDM, which most often require special support structures to fabricate overhanging designs, SLS does not need a separate feeder for support material because the part being constructed is surrounded by unsintered powder at all times. This allows for the construction of previously impossible geometries. Also, since the machine's chamber is always filled with powder material the fabrication of multiple parts has a far lower impact on the overall difficulty and price of the design because through a technique known as 'Nesting', where multiple parts can be positioned to fit within the boundaries of the machine. One design aspect which should be observed however is that with SLS it is 'impossible' to fabricate a

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hollow but fully enclosed element. This is because the unsintered powder within the element could not be drained.

The quality of printed structures depends on the various factors include powder properties such as particle size and shape, density, roughness, and porosity. Furthermore, the particle distribution and their thermal properties affect a lot on the flowability of the powder.

Fig.11. Sintersation 2500 system [52]

Commercially-available materials used in SLS come in powder form and include, but are not limited to, polymers such as polyamides (PA), polystyrenes (PS), thermoplastic elastomers (TPE), and polyaryletherketones (PAEK). Polyamides are the most commonly used SLS materials due to their ideal sintering behavior as a semi-crystalline thermoplastic, resulting in parts with desirable mechanical properties. Polycarbonate (PC) is a material of high interest for SLS due to its high toughness, thermal stability, and flame resistance; however, such amorphous polymers processed by SLS tend to result in parts with diminished mechanical properties, dimensional accuracy and thus are limited to applications where these

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are of low importance. Metal materials are not commonly used in SLS since the development of selective laser melting.

Sintering in SLS primarily occurs in the liquid state when the powder particles forms a micro-melt layer at the surface, resulting in a reduction in viscosity and the formation of a concave radial bridge between particles, known as necking, due to the material's response to lower its surface energy. In the case of coated powders, the purpose of the laser is to melt the surface coating which will act as a binder. Solid state sintering is also a contributing factor, albeit with a much-reduced influence, and occurs at temperatures below the melting temperature of the material. The principal driving force behind the process is again the material's response to lower its free energy state resulting in diffusion of molecules across particles.

SLS manufacturing applications are used in the aerospace industry, in applications medical, orthopedics, dentistry. The process begins by using CAD files, in the form of .stl file and the 3D part is printed layer by layer, usually having thicknesses between 20 and 100 of micrometers, creating a 2D image of each layer.

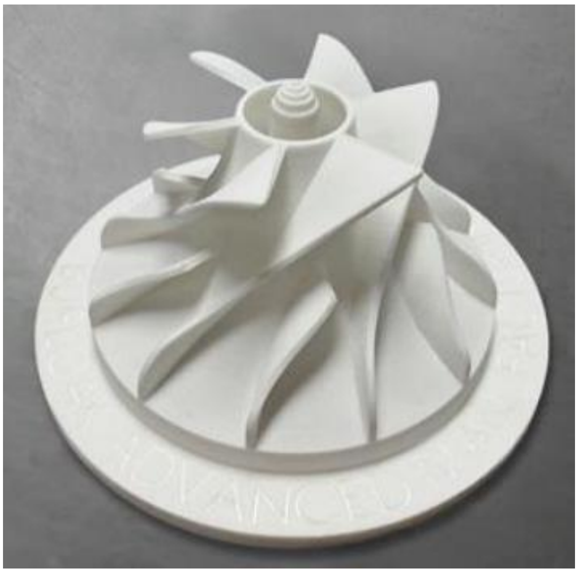

Fig.12. Industrial part with complex forms manufactured by SLS [53]

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The selective laser sintering process has some particularities, namely the metal powders used are pre-treated by conditioning them with a resin or with a polymer, i.e. the powder grains are film-coated, finally obtaining a new powder which contains 75-80% metal and 20-25% resin or polymer.

Another characteristic specific to the selective laser sintering process is the fact that the process takes place in two stages, in the first stage the very raw-green part is made brittle by melting the resin or polymer film of the grains and partially binding a metal particles between them through bridges and the second post-sintering stage in the furnace sintering at temperatures of 1100-1200ºC, producing the welding of metal particles between them and the consolidation of the whole structure. [1:37-52]

The metallic structure obtained is porous, having a density of 70-75%, presenting very good physical-mechanical properties so that these parts can be used as functional parts (sliding bearings, filter elements). [53,54]

In figure 12 is presented an industrial part with complex forms manufactured by SLS.

After the piece has been completed, a rest time (sometimes quite long) for reducing the temperature from tens or hundreds of degrees, the volume of powder what was subjected to processing. Then the piston of the cylinder in which the part was built rises in view of the evacuation of the piece. The final part together with the unsintered powder is transferred into an auxiliary machine equipment, in order to clean and remove excess dust.

The materials used in the selective laser sintering process are particularly various, starting with polyamide powders (DuraForm PA, PA1500, PA2200, PA1300GF, PA3200GF), metal powders (MC3201, DirectMetal 50-VI, DirectMetal 100-VI, RapidSteel 1.0, RapidSteel 2.0), quartz or zirconium-based powders (EOSINT S quartz, EOSINT zircon HT). [1:37-51]

Depending on the type of material to be sintered, there will be different power values of the laser used for sintering, respectively different sintering temperatures.

Selective laser sintering SLS, is a family of methods that can build a solid body from various types of powders (plastic, metal, ceramics including very rare metals or with physical-

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mechanical properties and of special biocompatibility) by solidifying the powder, following exposure successive layers of powders to a laser beam of various powers.
Through these processes, depending on the material, we can obtain a density of up to 100% and material properties comparable to those of conventional methods can be obtained manufacturing. [1:37-51]
Thus, SLS technology can successfully meet new challenges in terms of innovative technologies, in the context of a globalized economy and increased competitiveness.

1.2.9. Direct Metal Laser Sintering (DMLS)

The DMLS manufacturing process is part of LENS (Laser Engineered Net Shaping) from the selective laser melting category. [1,57,58]

Fig.13. Phenix Systems ProX DMP 100 Dental [59]

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The DMLS process has been developed and researched down to the manufacturing system level by the EOS company from Germany, since 1995.

This company made the most famous DMLS sintering equipment in the world and is one of the best performing sintering manufacturing companies.

A very diverse number of materials are available to be used with high-tech EOSINT M270 systems, offering a wide range of e-Manufacturing applications.

EOS CobaltChrome MP1, is a cobalt-chromium superalloy powder that was special optimized for processing on this type of high-tech systems. [1,57,58]

Other materials are also available for EOSINT M systems, including a special cobalt-chromium-molybdenum alloy for dental restorations.

The DMLS manufacturing process is identical to that of SLM selective laser melting, because it starts from the same 3D model of the part, which is sectioned into sections with thicknesses of 20 µm, forming the sequence of sections necessary for the physical materialization of the 3D model virtual. The very small thickness of 20 µm of the material section allows good sintering and leads to an increase in dimensional accuracy and the quality of the machined surfaces of the part, relative to other similar processes. [1,57,58]

In case of SLS technology, the metallic powders are not filmized, and the process is carried out in one step. In figure 12 is presented Phenix Dental ProX DMP 100 Systems.

However, when using low laser powers of 50 W a post treatment is required, by placing the part in a sintering furnace at a temperature between 800-900ºC for half an hour, for the increase in hardness and the improvement in mechanical and corrosion resistance.

In rapport with the SLM selective laser melting process, DMLS process used for manufacturing only metal alloys.

The metal powders that can be used in manufacturing through DMLS, include a large variety of materials including implantable or general-purpose stainless steel, superalloys cobalt chrome, inconel 625, inconel 718, AlSi10Mg aluminum alloys, titanium alloys- Ti6Al4V.

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Laser power on Phenix Systems manufacturing equipment varies from 50-500 W, which provides the energy needed to melt the powder layer for the materialization of a section.
Phenix Dental Systems use stainless steels 316L (ST4404D), hard tool steels (ST2709B), Co-Cr superalloys (ST2724G), Ti alloys, precious metals and non-ferrous alloys. [1,57,58,59]
The ProX DMP 100 Dental manufacturing system from figure 13 is used at rapid fabrication by direct metal laser sintering. This procedure allows direct production of fixed or removable prostheses from Co-Cr.
The machine is equipped with a platen from stainless steel, having circular or rectangular form. In this case, the platen has square form with the dimensions 100x100 mm and allows to print, only small parts, as in figure 14. [1,57,58,59]
After each use due to the high temperatures of 1300-1600^{o}C, the metallic powders adhere on the platen, respectively the supports of the welded parts remain, and the platens must to be changed or reused.

Fig.14. Platen of ProX DMP 100 Dental

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All materials intended for DMLS process have special physical and mechanical qualities, better than cast or forged materials, so they are recommended for biomedical implants, parts for design, architecture, robotics, tooling, aeronautical or automotive industry. In figure 15 is presented analogue dental implants manufactured via DMLS.

Fig.15. Analogue dental implants manufactured via DMLS

The properties of biocompatibility, corrosion resistance and low specific gravity, combined with the infinite possibility of 3D geometric modeling recommend this manufacturing process as a working tool of the future of micro-mechanical, mechatronic and robotics. [1,57,58,59]

1.2.10. Selective Laser Melting (SLM)

SLM selective laser melting has been grouped under the process category of "laser sintering" although this is improper, recognized because the process melts the powder, unlike selective laser sintering (SLS) and direct metal laser sintering (DMLS), which are true sintering processes. A similar process is electron beam melting (EBM), which uses a beam of electrons as an energy source. [1.62]

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The Fraunhofer Institute from Aachen patented this process of selective laser melting in 1995. Patent authors Dr. W. Meiners and Dr. D. Fockele not only have researched and patented this process, but they also contributed to the establishment of companies that produce and today these systems.

This process only processes metal powders of great diversity (powders of titanium and its alloys, alloy steel, stainless steel, tool steel, Co-Cr alloys, aluminium), having a very fine powder granulation below 20 µm. The powder used is obtained by atomization, having spherical granulation. [1.62]

Fig.16. SLM500 HL system [64]

Most SLM machines use working enclosures with dimensions of 250x250x350 mm, and the larger machines have enclosure dimensions of 500x500x500 mm.

Selective laser melting SLM is an additive manufacturing process, similar to the SLS selective laser sintering process, but at a higher level than it.

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The room in which the procedure is carried out contains a well-controlled atmosphere of inert gas, argon or nitrogen, at the oxygen level below 500 parts per million. [1.62]
Once each layer has been distributed, each 2D section of the geometry is melted by selective melting of the powder. This is done with a high-power laser beam, usually a ytterbium Yb fiber laser (100-200 W). In figure 17 is shown pre-assembled micro-turbojet engine of Inconel 718 manufactured by SLM.

Fig.17. Pre-assembled micro-turbojet engine of Inconel 718 manufactured by SLM [122]

Parts obtained by SLM technology do not require post-sintering treatment in furnace, the density of the part is almost 100% and it has practically mechanical properties identical to the properties of parts obtained by classical processes such as casting.
Parts with complex geometric shapes and details can be made with this technology (cooling channels for active die elements, for example) that are difficult to achieve through classic technologies. Figure 16 shows the SLM500 HL system. [64]

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This technology has manufacturing applications in aerospace, automotive, architecture or medicine fields (creates the possibility of manufacturing the customized orthopedic implants from biocompatible Ti materials) and is being pioneered. [1,62,63]

The ability to produce parts extremely quickly, economically and flexibly, it allows the manufacture of individual parts or batches, which in turn allow identification design or manufacturing issues at an early stage of development of the product, and the time to market is shortened. This new technology is used in top fields, fields of engineering and medicine, both for civil and military purposes.

The world's most advanced engineering entity, NASA, uses the technology EOSINT M270 Titanium Version.

1.2.11. Electron Beam Melting (EBM)

Electron-beam additive manufacturing, or electron-beam melting (EBM) is a type of additive manufacturing, or 3D printing, for metal parts. The raw material (metal powder or wire) is placed under a vacuum and fused together from heating by an electron beam. This technique is distinct from selective laser sintering as the raw material fuses having completely melted.

Metal powders can be consolidated into a solid mass using an electron beam as the heat source. Parts are manufactured by melting metal powder, layer by layer, with an electron beam in a high vacuum.

This powder bed method produces fully dense metal parts directly from metal powder with characteristics of the target material. The EBM machine reads data from a 3D CAD model and lays down successive layers of powdered material. These layers are melted together utilizing a computer-controlled electron beam. In this way it builds up the parts. The process takes place under vacuum, which makes it suited to manufacture parts in reactive materials with a high affinity for oxygen, e.g. titanium. The process is known to operate at higher temperatures

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(up to 1000 °C), which can lead to differences in phase formation though solidification and solid-state phase transformation.

Currently commercial materials for EBM include commercially pure Titanium, Ti-6Al-4V, CoCr, Inconel 718, and Inconel 625.

Other notable developments have focused on the development of process parameters to produce parts out of alloys such as copper, niobium, Al 2024, bulk metallic glass, stainless steel, and titanium aluminide.

1.2.12. Powder bed and inkjet head 3D printing

This technology was first developed at the Massachusetts Institute of Technology and patented in 1993. Binder jet 3D printing, known variously as "Powder bed and inkjet" and "drop-on-powder" printing, is a rapid prototyping and additive manufacturing technology for making objects described by digital data such as a CAD file.

Fig.18. Zprinter310 Plus system

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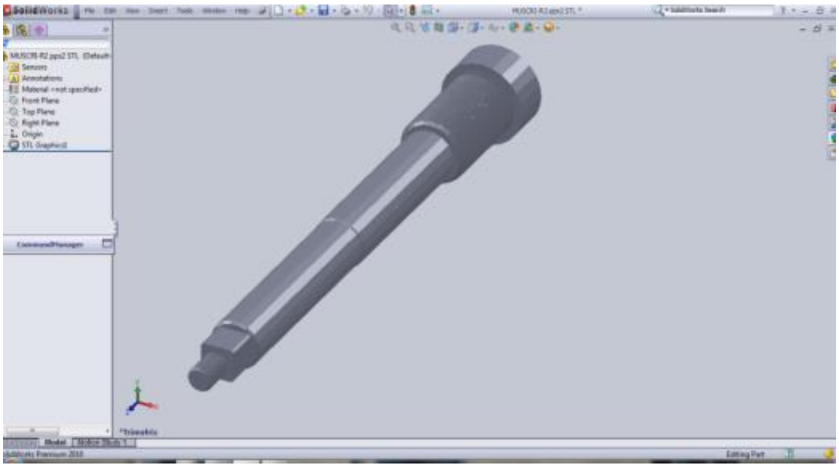

Fig.19. stl. file of the shaft

Parts printed using the binder jetting process are inherently porous and have an unfinished surface, as unlike powder bed fusion the powders are not physically melted and are joined by a binding agent. While the usage of a binding agent allows for high melting temperature (e.g. ceramic) and heat-sensitive (e.g. polymer) materials to be powdered and used for additive manufacturing, binder jetting parts require additional post-processing that can require more time than it takes to print the part, such as curing, sintering, and additional finishing.

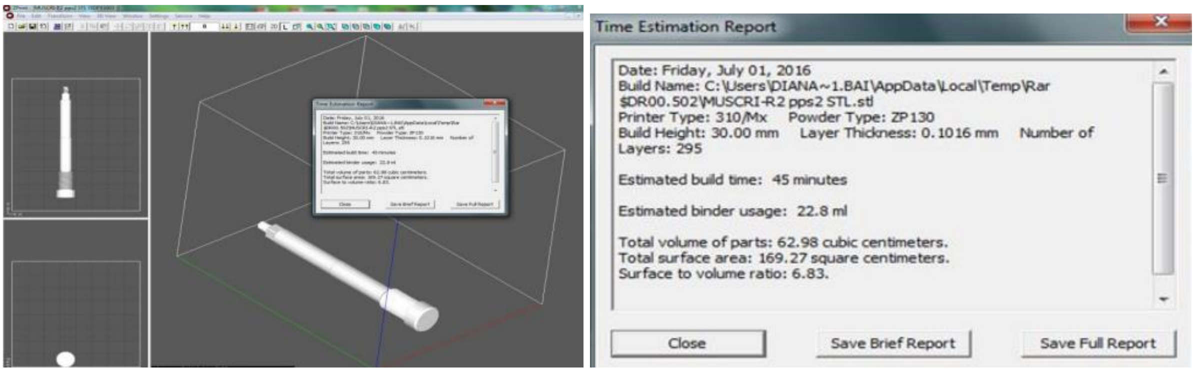

Fig.20. Estimation of time and consumption of powder and binder required for 3D printing

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In figure 18 the part obtained by 3D printing using the ZPRINT 310 Plus system, after cleaning and impregnation with resin and hardener. In figure 19 is shown the stl file for the shaft.
The ZPRINT 310 Plus software estimates the time required for 3D printing (45 min) for shaft part, tells us how much powder (62.98 cm^3) and binder (22.8 ml) are consumed during printing, as in fig.20. The software permit also to view the 2D sections layer by layer print, as in fig.21.

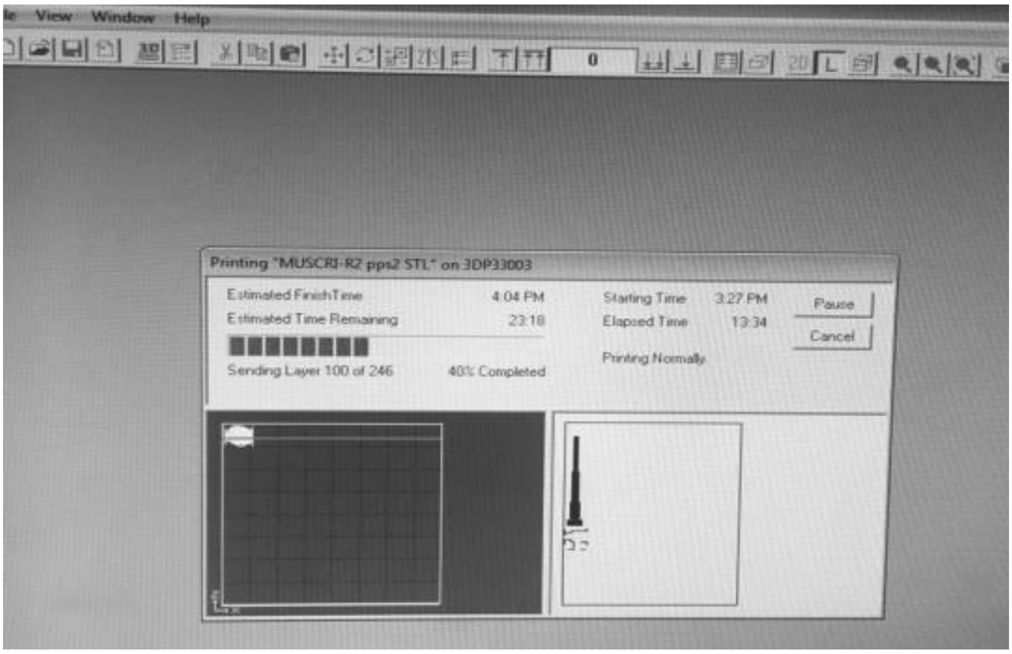

Fig.21. View of the 2D sections layer by layer during the printing process

It is noted that the powder has a fine granulation of the order of microns of 20-50 µm, with rounded grains, with a range of quite large particle size fractions.

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In figure 22 is presented the shaft model part manufactured from calcium carbonate powder by Binder Jetting using Zprint 310 Plus system.

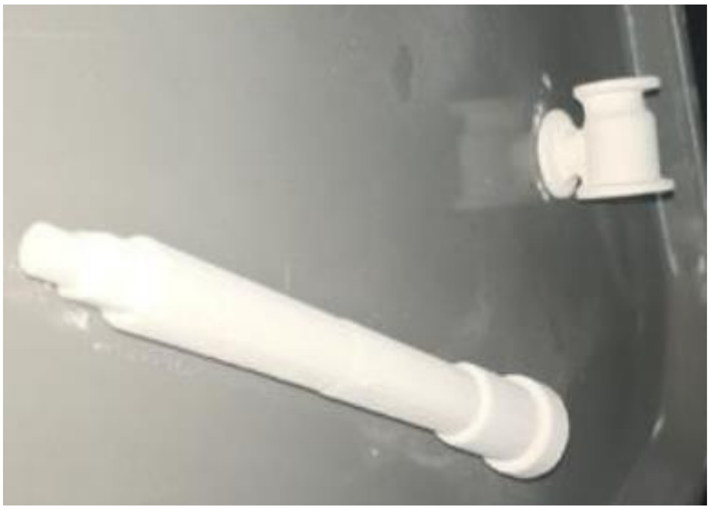

Fig.22. Industrial part manufactured by Binder Jetting using Zprint 310 Plus system

1.3.Plastic materials used in Additive Manufacturing

ABS and PLA are the most common FDM (Fused Deposition Modeling) printed materials and are typically similar in cost. ABS has superior mechanical properties but is harder to print compared to PLA. PLA is ideal for 3D prints where aesthetics is important.

Table 3. 1. The mechanical properties of Acrylonitrile Butadiene Styrene (ABS)

Properties	**Values**	**Units**
Density	1.0-1.4	g/cm3
Poisson's Ratio	0.35	-
Shear Modulus G	1,03-1,07	GPa
Melting Temperature	200	ºC
Glass transition temperature	105	ºC
Thermal Conductivity	0,25	W/m-K

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Extruded Temperature	200-230	ºC
Heat Deflection Temperature, 1,81 MPa	81	ºC
Young's modulus	1,79-3,2	GPa
Tensile Strength	29,8-43	MPa
Compressive Strength	76-78	MPa
Elongation at Break	10-50	%
Flexural modulus	2,1-7,6	GPa
Hardness Shore D	100	
Izod Impact Strength	58	kJ/m2
Yield Strength	28-120	MPa
Standard Tolerance	+/-0.05	mm
Biodegradable	-	-
Melt flow	12-23	g/10min
Rockwell Hardness	R102-R104	

Due to its lower printing temperature is easier to print with and therefore better suited for parts with fine details. ABS is best suited for applications where strength, ductility, machinability and thermal stability are required. ABS is more prone to warping. The mechanical properties of ABS are presented in Table 3.1. [1-86]

Other materials used frequently in FDM technology are the filaments of Polyethylene Terephthalate PET $(C_{10}H_8O_4)_n$ and Polyethylene Terephthalate Glycol (PETG). The mechanical properties of PET material are presented in the Table 3.2 and the comparison concerning mechanical properties between the common materials used in FDM technology, PLA, ABS and HIPS is shown in the Table 3.4. In table 3.3 are shown the mechanical properties of PLA for 3D printed material.

Table 3.2. The mechanical properties of Polyethylene Terephthalate PET $(C_{10}H_8O_4)_n$

No	Mechanical and chemical properties	U.M.	Value (unit)	Obs.
1	Density	g/cm^3	1.455 – cristalin 1.37 - amorphous	1.38 – at 20ºC
2	Tensile Strength	N/mm^2	74-cristalin 55-amorphous	-
3	Compressive Strength	N/mm^2	125	-
4	Flexural strength	N/mm^2	90	-
5	Torsion strength	N/mm^2	-	-

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6	Shear strength	N/mm^2	-	-
7	Elongation at break	%	50-cristalin 150-300 - amorphous	-
8	Ball penetration hardness	Kg/m^3	1370	-
9	Rockwell Hardness	-	R100-cristalin R90-amorphous	-
10	Charpy shock resistant (uncracked)	kJ/m^2	3.6	-
11	Charpy shock resistant (cracked)	kJ/m^2	2.5	-
12	Melting temperature	ºC	260	-
13	Glass transition temperature	ºC	67-81	-
14	Notch test	kJ/m^2	3.6	-
15	Vicat Temperature(VST)	ºC	82	-
16	Extruded temperature	ºC	220-250	-
17	Liniar expansion coefficient	-	7	$(*10^{-5}K^{-1})$
18	Specific Heat	cal/gºC	0.28	$(JK^{-1}*kg^{-1})$
19	Thermal conductivity	W/mK	0.15-0.24	-
20	Boiling point	ºC	350	-
21	Volume resistivity	Ω*cm	$4*10^{16}$ – cristalin $2*10^{16}$ - amorphous	-
22	Surface resistivity	Ω	10^{13}	-
23	Water absorption (ASTM)	%	0.5-0.6 – cristalin 0.6-0.7 -amorphous	/24h
24	Viscosity	cP	75000-90000	Low-viscosity PET at high-viscosity PET
25	Dielectric rigidity	kV/mm	16	-
26	Melt flow	g/10min	35,08	230ºC
27	Young's Modulus (*E*)	MPa	2800-3100	-
28	IZOD Impact strength	J/m2	140	-

Table 3.3. The mechanical properties of PLA (Polylactic Acid)

Properties	Values	Units
Density	1.25	g/cm3
Poisson's Ratio	0.36	-
Shear Modulus G	2.4	GPa
Melting Temperature	173	ºC
Glass transition temperature	60	ºC
Thermal Conductivity	0.13	W/m-K
Extruded Temperature	160-220	ºC
Heat Resistance	110	ºC

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Young's modulus	3.5	GPa
Tensile Strength	61.5	MPa
Compressive Strength	93.8	MPa
Elongation at Break	6	%
Flexural strength	88.8	MPa
Hardness Shore D	85	A
Impact Strength	30.8	kJ/m2
Yield Strength	60	MPa
Standard Tolerance	+/-0.05	mm
Biodegradable	yes	-

Table 3.4. Comparison concerning mechanical properties between the common materials used in FDM technology, PLA, ABS and HIPS

Polymers	HIPS			ABS			PLA		
	OV	SD	SE$\bar{x}$	OV	SD	SE$\bar{x}$	OV	SD	SE$\bar{x}$
MFI (g/10 min)	7.5 ± 0.20	0.16	0.11	8.76 ± 0.16	0.13	0.09	13.52 ± 0.11	0.09	0.06
Young's modulus (MPa)	112.5 ± 0.12	0.09	0.06	175 ± 0.11	0.09	0.06	47.9 ± 0.10	0.08	0.05
Yield stress (MPa)	3.44 ± 0.21	0.17	0.12	0.49 ± 0.21	0.17	0.12	0.27 ± 0.16	0.13	0.09
Glass transition temp (°C)	100.41 ± 0.16	0.13	0.09	109.76 ± 0.2	0.16	0.11	62.57 ± 0.21	0.17	0.12
Peak load (N)	80.8 ± 0.11	0.08	0.06	207 ± 0.2	0.16	0.11	282.4 ± 0.20	0.16	0.11
Peak strength (MPa)	4.21 ± 0.16	0.13	0.09	10.78 ± 0.11	0.09	0.06	14.71 ± 0.16	0.13	0.09
Peak elongation (mm)	1.9 ± 0.20	0.16	0.11	4.75 ± 0.16	0.13	0.09	5.13 ± 0.16	0.13	0.09
Percentage elongation at peak (%)	3.0 ± 0.11	0.09	0.06	6.0 ± 0.15	0.12	0.08	7.0 ± 0.10	0.08	0.05

In the SLA (Stereolithography) and DLP (Digital Light Processing) technologies are used photocurable vinyl- or epoxy- functional oligomers for photopolymerization.

In table 5 are presented the mechanical properties of Bisphenol A Ethoxylate Diacrylate resin. Other resins used in SLA manufacturing are the polyurethane resins. In figure 4 can remark the SEM image for the resin sample. [1-86]

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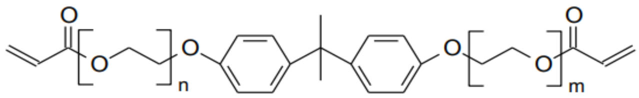
Table 5. The mechanical properties of Bisphenol A Ethoxylate Diacrylate

Bisphenol A Ethoxylate Diacrylate



n + m ~ 4

INTRODUCTION

EBECRYL 150 is an ethoxylated bisphenol A diacrylate commonly used as reactive diluent in UV/EB cure applications. EBECRYL 150 can improve the cure response, hardness, and chemical resistance of UV/EB curable coatings and inks while maintaining good adhesion, and without imparting brittleness.

PERFORMANCE HIGHLIGHTS

EBECRYL 150 is characterized by:

- High reactivity
- Moderate viscosity
- High refractive index

UV/EB curable formulated products containing EBECRYL 150 are characterized by:

- Hardness
- Chemical resistance
- Good adhesion
- Improved wetting

The actual properties of UV/EB cured products also depend on the selection of other formulation components such as oligomers, additives and photoinitiators.

SPECIFICATIONS(1)	VALUE
Acid value, mg KOH/g, max.	5
Appearance	Clear liquid
Color, Gardner scale, max.	2
Viscosity, 25°C, cP/mPa·s	1150-1650

TYPICAL PHYSICAL PROPERTIES	
Density, g/ml at 25°C	1.14
Flash point, Setaflash, °C	>100
Functionality, theoretical	2
Refractive index (n_D at 20°C)	1.5294
Vapor pressure, mm Hg at 20°C	<0.01

TYPICAL CURED PROPERTIES(2)	
Tensile strength, psi (MPa)	6300 (43)
Elongation at break, %	9
Young's modulus, psi (MPa)	180000 (1241)
Glass transition temperature, °C(3)	41

Characteristics of the powder particles used in additive laser manufacturing, using different standards,-are shown in Table 6.

Table 6. Standards (ASTM, ISO, EN) for powder properties used in additive manufacturing [86]

AM Powder characteristics	Powder Type	Symbols	Techniques	ASMT Standard	ISO Standard	EN Standard
Size and shape	Metallic powders	Φ [μm]	SEM	B822	13322	-
Specific density	Metallic powders	$\rho_{specific}$ [g/cm^3]	Gas pycnometer	B293	12154	-
Apparent density	Non-free flowing metallic powders	ρ_{app} [g/cm^3]	Hall apparatus	B212	3923/1	3923

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Apparent density	Non-free flowing metallic powders	ρ_{app} [g/cm^3]	Carney apparatus	B417	3923/1, 4490	4490
Apparent density	Metallic powders	ρ_{app} [g/cm^3]	Arnold meter	B703	-	-
Apparent density	Refractory metals and compounds	ρ_{app} [g/cm^3]	Scott volumeter	B329	3923/2	-
Tap density	Metallic powders	P_{tapped} [g/cm^3]	BT-1000	B527	3953	3953
Average particle size	Metallic powders	d_{60}	Fisher sub-sieve sizer	B330, C72	10070	-
Powder sieve analysis	Metallic powders	-	Sieve analysis equipment Westmoreland	B214	4497,2591	24497
Particle size distribution	Metallic powders and related compounds	d_{10}, d_{60}, d_{90}	Light scattering	B822	13320, 24370	-
Flowing rate	Free-flowing metallic powders	Flow time (s) for 50g	Hall apparatus	B213	4490	4490
Envelope specific surface	Powder bed under steady flow	S_v [m^2/g]	Measurement of air permeability	-	10070	196-6

The main mechanical characteristics of Ti6Al4V powder are: elastic limit 0.2% $Rp_{0,2}$= 815 MPa, elongation at break = 10%, Vickers hardness = 375 HV , elastic modulus = 229 GPa, mass density = 8,336 g/cm^3, corrosion resistance < 4 µg/cm^2, and thermal expansion coefficient = 14,5×10^{-6} K^{-1}.

The SINT-TECH company and ISO 9001 and ISO 13485 standards propose a range of powders suitable for the process developed by Phenix Systems. This powder range was selected to guarantee an optimized result for implementation with the "PX" range and the former "PM" range systems produced by Phenix Systems. [1-86]

The Co-Cr alloy powder (ST2724G) used for DMLS manufacturing presents the chemical composition: 54.31 %Co; 23.08%Cr; 11.12% Mo, 7.85% W, 3.35% Si, and Mn, Fe < 0.1%. [35-41]. Table 7 presents the mechanical characteristics of the Co-Cr powder used for the DMLS manufacturing process.

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Table 7. Mechanical characteristics of Co-Cr powder

Minimum layer thickness	20 µm
Surface roughness	Ra=10 µm, Ry=40-50 µm Ra=0,39 µm, Rz=1,6 µm After polishing Rz<1 µm
Density with standard parameters	8,3 g/cm^3
Mechanical properties	
Tensile strength	1100MPa
Yield strength	600 MPa
Elongation at break	20%
Young's modulus	200 GPa
Hardness	35-35 HRC
Fatigue life	>10 million cycles
Thermal properties	
Maximum operating temperature	1150 ^{0}C

In Table 8 are presented the mechanical properties of the materials used in Selective Laser Melting technology.

Table 8. Properties of metallic materials used in SLM technology [82]

Material	Property	Value
Inconel 625	Density	8.44 g/cm^3
	Yield strength	460 MPa
	Modulus	205.8 GPa
	Density	4.43 g/cm^3
TiAl64V	Yield strength	880 MPa
	Modulus	193 GPa
	Density	8 g/cm^3
Stainless steel	Yield strength	205 MPa
	Modulus	193 GPa
	Density	2.67 g/cm^3
AlSi10Mg	Yield strength	240 MPa
	Modulus	70 GPa

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