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DIGITAL AESTHETIC OF NEW PRODUCTS OBTAINED BY SELECTIVE LASER MELTING PROCESS

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Abstract

Additive Manufacturing processes are rapidly evolving in order to enable their increasing diffusion in all those industrial contexts where a flexible, customized and low volume production is needed. The research is focused on processes that use metal powders.

Such manufacturing techniques allow achieving illusory shapes free from any geometrical and productive constraints, thus fostering a new conception of production based on the digital aesthetic. This revolution is expressed by the digitalization of manufacturing processes which opens the way to a direct production from 3D model to the real object and therefore to a new way of thinking, designing and producing objects. This new production requires also new rules and guidelines for a product design. The purpose of work is to illustrate the state of the art of selective laser melting techniques based on metal deposition, highlighting the critical issues such technical limitations and the designing rules for a mass production. It is necessary to point out sensible future industrial applications, the social impact that this technology can have.

Keywords: Design process, Industrial design, New product development, Selective laser melting, Metal powder

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INTRODUCTION

If we had to portrait the technological production landscape what would we see? It is possible to notice how the context, rich of new kinds of design and production, is characterized by an increasing interest of additive manufacturing technologies (AM) (Gibson et al, 2010) and the digital evolution is promoted by technological development. This progress leads to a new economical and productive paradigm: while the AM technologies change the manufacturing world from a design and production view, a new type of products come up in both creation, use, and dismissal. The digitalization of processes represents a real revolution for the manufacturing system, allowing to a large number of users access to these technologies. Typical consumers are experts, acknowledged of production and modelling methodology. The quick spreading of 3D printing, encouraged by a technological democratization through cheap and small 3D printers, becomes more and more popular, together with the availability of online printing services. Physical spaces (like FabLab) arise (Gershenfeld, N., 2008). Artists, designers, craftsmen, approach the 3D printing production to investigate new shapes, new manufacturing methods and materials. The growing interest about these processes is increased by the possibilities of these processes compared to conventional ones. The traditional constraints are overcome, and this guarantees flexibility to the production. A big design and production fertility is the mark of this emerging context: in fact it is possible to name it a “Third Industrial Revolution” (Special Report, April 2012). A new professional arises: the maker. The maker, or technological craftsman, is the one that creates, virtually models and realizes his ideas. The additive technologies, identified in regulations ASTM F2792 in 2009 (Committee F42, 2009, ASTM F2792, Standard Terminology for Additive Manufacturing Technologies[1,2]. United States), are all the technologies that, “a process of joining materials to make objects from 3D model data, usually layer upon layer”, create objects. This field has mainly two branches: metallic materials and polymeric ones. Metallic materials are mainly used for the production of components, while polymers are used to realize prototypes for formal and functional studies since 3D printing is so flexible and adaptable, suitable to different situations. The democratization of 3D printing, specifically the FDM, has made this process a pioneer of the “do it yourself” movement. This definition marks a new and revolutionary way of designing and producing objects. A new generation of products is born under a new aesthetic, the digital aesthetic. To better understand the context, a distinction between the many different types of processes and equipment used in this field is necessary.

Table 1. Average costs regarding to the additive manufacturing process

Polymers		Metals	
Technology	Cost (Ml/€)	Technology	Cost (Ml/€)
Fused deposition modelling (FDM)	0,6 - 10	Laser cladding	100 – 200
3D Printing	10 – 50	Selective laser melting (SLM)	300 – 1000
Stereolithography (SLA)	4- 500		
Selective laser sintering (SLS)	300 - 500	Selective laser sintering (SLS)	300 - 500

Table 1 details processes and related costs referred to different technologies and equipment. It is evident that the more complex the system and the processes selected, the higher become the costs. Makers machines like FDM, cost approximately € 600-1000, thus 3D printers become accessible to a wider public. Table 2 gives more details about machine classes, operators skills and costs (Gebhardt, A., 2011)

Table 2. Class of machine

Class of Machine	Operator	Infrastructure	Cost
Fabbers	Everyone with basic skills to operate a personal computer	Apart from a kitchen table no infrastructure is required	From under €/$ 1.000 to €/$ 20.000
Office Printers	People who professionally work with different types of 3D CAD	No special infrastructure is required. A separate office room helps to handle the material and the parts and keeps away the (not really bothering) noise	From €/$ 15.000 to €/$ 140.000
Shop floor machine	Technicians of the fabrication department	A shop floor environment is needed	From €/$ 120.000 to €/$ 800.000 and up

As shown in the Table 2, for each technology the equipment can be divided in three macro groups: fabbers, office printers and shops floor. It remarkable that, for each of the three identified categories, costs, operator skills and required space change. Skill levels varies from the inexpert user to professionals with expertise in machine management. Concerning work space volumes, it ranges from small rooms (e.g. a family room without any dedicated space), to structures providing equipped platforms. The selective laser melting (SLM) derives from the selective laser sintering (SLS). In particular SLM melts metal powder to create fully melted parts. The SLM allows to obtain metal products with complex shapes, it is a very flexible technology and the products can be customized accordingly to the user's needs. The absence of moulds permits more formal experimentation, because the traditional design and production constraints are overcome. For instance undercuts and spare pieces can be produced. Complex geometries also means the ability to achieve articulated structures with variable density, or very small trabecular mesh, similar to bone's internal porosity. In some cases these kinds of elements can become a structural element of the realized component. The high flexibility of SLM also leads to test these structures inspired by nature and imitate their function. Velcro and gecko are two examples of imitations. SLM reproduces the micro structures, otherwise impossible to be produced. The possibility to obtain lightweight structures also allows to obtain light parts without compromising the mechanical strength. Besides the possibilities provided, the printed area and the production time in SLM can be considered as disadvantages. The first presents limited size and constrains: it is possible to produce small pieces to be assembled in a second phase. Usually the printed area is about 250x250 mm with a variable height between 250 and 325 mm, depending on the machine. Leading companies in the market are EOS GmbH, Concept Laser, Renishaw SLM Solution, Realizer. The production timing must be analysed regarding to the component complexity and the batch production. SLM is a technology that makes possible to obtain products with dimensional tolerances, ranging between 0.002 mm and 0.202 mm (Cooke et al., 2010). The resulting surfaces have a high surface roughness. The roughness R_a varies between 12 μm and 17 μm, before machining; subsequently the values vary between 1.5 μm and 4 μm (see Table 3) (Vaithilingam et al., 2012).

Table 3. Selective laser melting R_a

	R_a min (μm)	*R_a max (μm)*
R_a	*12*	*17*
R_a machining	*1,5*	*4*

1 AIMS OF THE WORK

The aim of this article is to give an overview on additive manufacturing (AM), more specifically selective laser melting (SLM) applied to metal products and the advantages and disadvantages about designing with it. The purpose of the paper is to make the analysis of the existing state of art for new emerging metallic products obtained SLM. In the paper products that are produced by using metallic powder are considered. Metallic powder is commonly used in aerospace and automotive applications but the paper is aimed at enlarging the perspective collecting different application fields where the SLM and metallic powder can be a challenge for design and production. This technology allows indeed new functions and structures that create a new kind of lighter, flexible and customizable products. From the analysis of the state of art a short overview of fundamental design guidelines, application fields and design steps are given. AM introduces a new way to think, design and producing objects overcoming the conventional constraints. The digitalization of the process allows the achievement of a new aesthetic defining these products.

2 PROCESSING TECNIQUES AND MATERIALS

SLM creates fully melted objects based on a powder bed technology. The manufacturing process consists of firstly a powder layer is deposited by a blade and then the selective melting of the powder by a laser. The laser path is dictated by a file tool path. The atomizing powder used for this process has a spherical shape with diameter between 20 µm and 50 µm. The grain size directly affects the thickness of the layer and this influences the geometry. The rounded shape of the powder permits a homogeneous distribution in the printed area. It is also important for the final roughness and precision of the product. Slicing direction, thermal loads and consequently deformations determine the dimensional and geometrical tolerances. During the process the printed area goes down and then a blade spreads another layer of powder. The process continues until the end of the product. The whole process is made under controlled atmosphere with the use of argon or nitrogen. These gases protect the metallic powder from oxidation, ensuring better features to the final product. From this point of view, SLM is a complex technology because both the process and the materials are difficult to manage. SLM works with metals and their alloys. The most investigated materials used for the emerging applications seen in the literature are titanium and aluminium alloys. Other materials are steel, bronze and gold. Copper is difficult to process, so it is not commonly used in its pure form. Gold is quite difficult to process and expensive, however, it is used to create jewellery, since in this field the formal and the functional experimentation have a lot of possibilities. The SLM products are mono material because it is possible to work with only one powder at a time. The powder is extended and not deposited, for this reason there is no control over the combination of the materials. Often the SLM machinery manufacturer sells directly the powders, in order to guarantee a major stability to the product and ensure the success of the process. After the choice of using metal the other important things are to identify if the mechanical properties have been compromised, because the deposited component is subject to cycles of heating and cooling. The products are submitted to functional tests like measurement of pressure resistance, high temperature resistance, wear resistance to assess the capabilities of products. The literature review shows the need to obtain pieces with mechanical properties comparable to the pieces realized by conventional technologies. The benchmark of Kurt (Kruth et al., 2005) underlines the mechanical property of SLM products obtained using different material-machinery combinations. The mechanical properties like stiffness, hardness, density, Young's modulus are some of the properties defining the full structure of the objects. It is also interesting to analyse if the AM technologies, considering the same shape of an object, can be compared with the traditional ones.

3 APPLICATIONS

The analysis of the context has shown that SLM can be used in different fields, such as: Design/consumer goods, Arts, Medical, Dental, Aerospace, Automotive and Energy. The application fields show how the SLM is a versatile and flexible technology. In common, these sectors request high level of customization in small batches. This condition permits a large formal and functional experimentation. Design and consumer goods consist of several kinds of products ranging from small components like jewellery to more complex products like tables or bicycle frame.

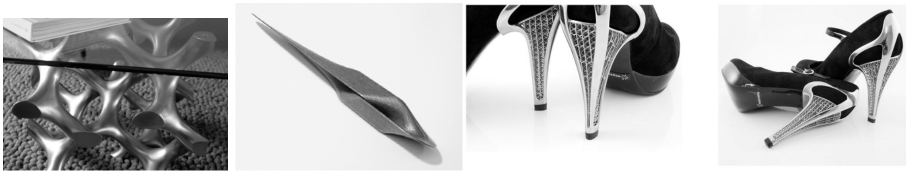

Figure 1. Design and consumer goods examples (MGX, Shapeways, Materialise)

In the arts field the experimentation is high, new shapes and materials can be investigated, usually unique pieces are made and so the cost constraint is overcome. The introduction of the SLM in medical field permits the realization of honeycomb structures, reproducing the porous bone-like structure, thus reducing the weight of the prosthesis. Tomographical body scanning techniques and parametric files guarantee a great personalization of the prosthesis. In the dental application the products have small dimensions and they are extremely customized.

Figure 2. Medical and dental examples (EOS Gmbh)

Finally, in the last three fields, it is possible to find formal, manufacturing and materials experimentations. The images shown in Figure 2 are an automotive exchanger and the redesign of a joint that satisfy the mechanical properties required by the respective pieces made by the conventional technologies.

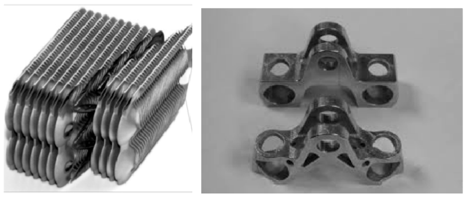

Figure 3. Aerospace and automotive examples (EOS Gmbh)

For SLM products it is essential to define the type of use. Three main categories have been identified: new products, tooling and spare parts. In the new products category all the products that are designed for SLM directly in the concept phase are included. Tooling category identifies tools and moulds that are redesigned. Thanks to SLM new features or enhancements to the existing features are possible. An example is the conformal channels that can be integrated into the traditional moulds. Such an integration in the cooling cycle allows a better distribution of the liquid and this improves the final product features obtained, for example, by injection moulding. Another example can be a specifically designed tool and this permits to obtain features not achievable with traditional processes, as such as stamping or bending. Spare parts are the replacement products which can be produced exactly when replacement for a component is required for such as in case of breakage or wear, thus avoiding the use of warehouses to stock spare parts.

4 DESIGN PROCESS

The phases that describe the manufacturing and design in SLM process are reduced compared to conventional manufacturing methods.

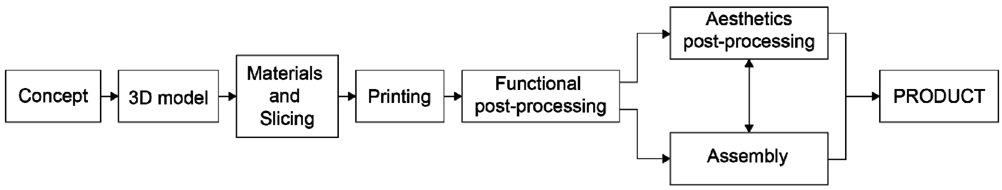

Figure 4. Design phases

As seen in Figure 4, the achievement of a good product is marked by a succession of steps that start from the concept and arrive to the production.

4.1 Design rules

The design or concept phase of the product becomes completely digital. This feature makes the process versatile, allowing the designer to modify the product on time. In the concept phase the project proposals that characterize the product and its design and formal guidelines are defined. The design phase can be divided into formal, aesthetic and functional phases. In the formal phase the requirements for the realization of a good product are defined. The formal design refers to the study of new forms that determinate the character of a product or at the same time the study of guidelines in a specific family of objects to create continuity of style. SLM allows high formal experimentation, creating new formal models that reflect some features now already specific to additive products. SLM has unique capabilities that are divided and defined by shape complexity, hierarchical complexity, functional complexity and material complexity. SLM allows lightweight structures, topology optimization, freeform design and customable parts. SLM can realize massive structures, but the main feature of this technology is its flexibility like the creation of honeycomb and foam structures. It is possible to define the optimal geometrical part if the design problem is overcoming by a good functional design (Ponche et al., 2014). Design guidelines (Kranz et al., 2015) include thin wall, the position in the printing area determines the accuracy of the layers and the surfaces. Besides it is also important to investigate how the support can be used, when the structures are self-supporting or when the angles are obligatory required (after 45°). *"Maximise product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies."* (Rosen et al., 2014)
SLM is characterized by several elements like:

- Powder dimension (20 μm – 50 μm)
- Fiber laser power (100 W – 400W)
- Gas: argon or nitrogen
- Laser beam spot diameter usually of the order 70 μm (higher such as 135 μm diameter for 400 W laser power).
  - Layer thickness (20 μm – 100 μm)
  - Single material

The Table 4 shows preliminary design rules that help designers to correctly draw the objects for SLM process.

Table 4. Design rules (Ponche et al., 2014, Kranz et al., 2015, Rosen et al., 2014, Samperi et al. 2014)

<table>
<tr><td>SHAPE COMPLEXITY (Capability to fabricate a layer is unrelated to the layer’s shape)</td></tr>
<tr><td>Orientation</td></tr>
<tr><td>• Support</td></tr>
<tr><td>• Slicing</td></tr>
<tr><td>• Surface quality
    • Under 45° needs supports
    • Less 45° poor surface quality, 90° best surface quality
    • Roughness: from 4 µm to 34 µm:
        • Upside 0°: 3-5 µm | 10°-90°: 10-13 µm
        • Downside 0°-40°: 10-12 µm | >50°: >13 µm | >70°: 23 µm < Ra < 32 µm</td></tr>
<tr><td>• Distortion and deformation</td></tr>
<tr><td>Shape Freedom</td></tr>
<tr><td>• Topological optimization, Lattice structures, Foam structures, Infinite form, Internal and conformal channel</td></tr>
<tr><td>Geometrical Freedom</td></tr>
<tr><td>• Undercuts</td></tr>
<tr><td>• Accuracy: +/- 0.02-0.05 mm (+/- 0.1-0.2%)</td></tr>
<tr><td>• Minimum wall thickness: 0,4 mm± 0,02 mm, wall thinner than 0,4 mm will not build</td></tr>
<tr><td>• Minimum size between features “gap”: 0,2 – 0,3 mm</td></tr>
<tr><td>• Minimum feature size: 0.04-0.2 mm</td></tr>
<tr><td>• Holes:
    • Smallest Ø 0,7mm parallel to the substrate
    • Smallest without support Ø 1mm, largest Ø 12mm needs supports (perpendicular)</td></tr>
<tr><td>Pins (internal): Minimum 0,8mm | 0,6 mm not rigid | Under 0,6 mm impossible to create</td></tr>
<tr><td>Density Freedom</td></tr>
<tr><td>• Porosity, Lattice structures, Variable and not homogeneous, Up to 99.9%</td></tr>
<tr><td>Support</td></tr>
<tr><td>• Ledge (impossible to create) | Chamfer (45°-55°-65°) – self-supporting | Convex radius (not possible to build tangential radii larger than 3 mm) – self-supporting | Concave radius (up to 2 mm) – self-supporting | Holes from 2 mm to 30 mm – self-supporting | Types (point, cylinder) | Post-processing (remove support) | Max. overhang without support: a ≤ 0,3 mm</td></tr>
<tr><td>Font</td></tr>
<tr><td>• Orientation | Up or down (extrusion or not) | Dimensions</td></tr>
<tr><td>HIERARCHICAL COMPLEXITY (Nano/microstructures, mesostructures, macrostructures)</td></tr>
<tr><td>• Multi-scale features</td></tr>
<tr><td>FUNCTIONAL COMPLEXITY (Fabricate operational mechanisms)</td></tr>
<tr><td>Gear</td></tr>
<tr><td>• Gear tooth separation ranges from 1.5 mm to 0.5 mm</td></tr>
<tr><td>Assembly</td></tr>
<tr><td>• Kinematic or functional elements (assembly and sub-assembly direct in the printing phase)</td></tr>
<tr><td>MATERIAL COMPLEXITY (To process the material differently at different points)</td></tr>
<tr><td>Materials</td></tr>
<tr><td>• Titanium, Aluminium, Steel, Gold, Bronze</td></tr>
</table>

Following the concept, the 3D model phase is found. In this phase all the features and dimensions are defined. In the digital data file all the guidelines that determine the shape and the functional characteristics are enclosed. In materials and slicing phases the material is chosen and the 3D model is divided into several layers. The number of the layers depends on the desirable accuracy of the final product. Design optimization of supports for overhanging structures in aluminium and titanium alloys by selective laser melting (Calignano, F., 2014). Then the printing phase follows, where the 3D model becomes a physical object. SLM products require functional post processing to improve their physical and mechanical properties. Thermal processes are required to eliminate any residual tension. Aesthetics post-processing and assembly phases depend on the product requirements. In the last phase the final product is obtained. In areas such as jewellery, or works of art, free and complex forms, without any production constraints can be obtained as seen in Figure 6.

Figure 6. Formal and lightening shapes (EOS Gmbh, Evan Riot)

The first example in Figure 6 (left) is a collaboration between EOS Gmbh and Cookson (EOS Gmbh). This product is known, as in its realization the absence of moulds eliminates the traditional constraints, such as undercuts. This ring was made in SLM because this technology allows to obtain invisible layers. However, the surfaces need post-processing to improve surface finish, in this case is polishing. Particularly, the required surface finish should meet the aesthetic requirements. At the same time, the ring is an example both of formal requests and of a new aesthetic expression. Gold, which is the chosen material, maintains its physical properties, without alteration and this is another feature. The jewellery usually is an object made by investment casting which guarantees the complete fusion of the metal and, in addition, the possible porosity and impurities are eliminated. Formal observation shows that the plasticity of the material, which seems manipulated by expert hands, becomes an illusory object that overcomes the limits of technology. Thus, it appears to be modelled on the user's hand, although no special tools are required for its realization. Another example of formal experiments and production capacity of SLM, is the work Graffiti Analysis, sculpture series in bronze, chrome and ABS thermoplastic Various 2009 (Evan Riot). It is possible to create new forms and the result is a new aesthetic, definable digital aesthetic. A further distinction can be made for objects with functional characteristics, such as the redesign of handles for aircraft (Figure 7).

Figure 7. Aerospace redesign optimization (EOS Gmbh)

The handle for aircraft seen in in Figure 7 is a collaboration between EOS GmbH and EADS for Airbus A320 aircraft (EOS Gmbh). The use of techniques such as topology optimization, allows to build products with mechanical properties comparable with the traditional technologies: in this case the piece is made by foundry. The redesign purpose of this element is to render the structure lighter by the reduction of the raw material, while the structural constraints are satisfied. Directly in the concept phase this approach leads to a reflection on the impact of these improvements on the entire product, the airplane, by improving its performance. An additional constraint is to maintain the level of safety during the use. The handle is in titanium; a material typically used for this kind of applications because it is light and possesses high mechanical properties. Furthermore titanium, unlike aluminium, does not oxidize at high altitude. The additive technologies and topological optimization introduce a new concept of lightness. Objects, lightened by the excess material, can be understood as functional structures.

4.2 Printing phase

The second phase of production is the printing phase. Here, the construction of the object takes shape, starting from a 3D file, up to a physical, real object. New elements, new types of objects with undercuts, complex and complicated structures are thus achievable, but new design rules have to be defined.

Figure 8. Complex structures (Shapeways)

The Figure 8 highlights how complex forms can be printed. From the left image it is possible in fact to see how the geometry is complex, in its inner part, where the structure is developed, while maintaining a hollow and light object. From the right image you can see how the decoration is not uniform, but the theme varies. These geometries are quite impossible, or very complex to realize with the traditional technologies. The examples shown here, however, can lead to a consideration about to the support material. For instance, if the geometry can be simplified to a slender object such as a shelf, very long compared to its point of attachment, it will be necessary to use a support that will be removed in post process. In the second picture you can see how hollow internal structures are achievable despite having irregular geometries, in this case a hole slightly arched.

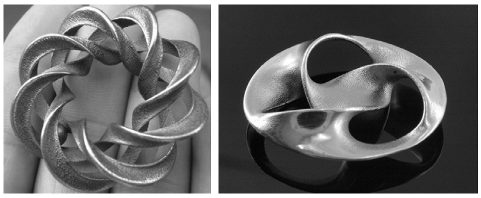

Figure 9. Infinite geometries (Shapeways)

The images in Figure 9 demonstrate that infinite geometries that are illusory geometries in the space, without real beginning and end are printable. The right image has a metallic structure that seems manually modelled giving plasticity and softness to the object. Some limitations arising from the use of SLM are the dimensions of the parts and the necessity of post processing to improve the surface finishing but above all the physical and mechanical characteristics of the piece. Furthermore the support material is required for unbalanced geometries. SLM still needs specifications about the repeatability of the process, since starting from the same 3D model, obtaining a correct geometry is not guaranteed. Another limitation in the construction phase is the use of a single material, so that only mono material objects can be created.

4.3 Assembly phase

The assembly phase for SLM especially in the case of small pieces is reduced. SLM allows building products already assembled in the printing phase, while connection elements are eliminated, but the necessary movements for a correct function of the product is still provided. The print area does not allow the printing of large dimensions. The example of large geometry is the frame of the bike MX6-EVO (Renishaw), collaboration between Empire Cycle and Renishaw (Figure 10).

Figure 10. Bicycle frame and printed configuration (Renishaw)

This product shows that the realization of a piece as large as the entire frame already assembled, with a single print is not possible, It is printed in different components, to be later assembled with an 3M industrial adhesive. This shows how the print area greatly affects the size of the piece but at the same time the SLM permits to simultaneously print several pieces.

4.4 Finishing phase

The products require post processing that can be made for functional or aesthetic purposes. Aesthetic post processing, such as polishing, painting, and brushing are used to improve its appearance. The functional post processing is used to increase the performance of the pieces. The surfaces can be investigated both from a technical and perceptual point of view. In the technical application, surfaces can be designed to improve the functional performance, to protect or connect product. From the analysis, it can be concluded that the components are characterized by high surface roughness, comparable to the pieces resulting from foundry processes, of which R_a varies from 12 μm to 17 μm (see Table 3) (Kruth et al, 2010). Final roughness R_a after machining varies from 1,5 μm to 4 μm.

5 CONCLUSION

The AM context, full of new technologies, allows the continuous production and technological development. Simpler technologies, such as FDM, already became part of the new production context, as well as the signature of a new mode of production. It is interesting to understand if more complex processes, such as SLM, may be part of this production revolution. From the analysis, we noted that the SLM is a complicated process, both in the management of the process and the materials. In addition SLM equipment has high cost that makes it less accessible to the public. The continuous technological progress leads to the hypothesis of a simplification of the process. A possible investigation could be directed towards the creation of economic systems, in order to render them makers' machines. The consequent socio and cultural impact is also an important aspect. The article proposed to understand the real design and production possibilities of metal products made by SLM. It emerged as a new class of products presenting the new digital aesthetic concept. Digital aesthetic indicates all the products that overcome the traditional production constraints are lightweight, free form and complex. Studies, such as topology optimization, allow the realization of lightweight objects, with mechanical properties comparable to the conventional ones. Some SLM characteristics such as roughness surface require further attention, as they are similar to the product surfaces coming from foundry. Commonly they need a functional and/or aesthetic post processing due to this reason. The technological improvements should take the requirements of the future industrial production into account and provide a compromise between technology and social impact. It is essential to understand whether SLM can become an inspiration or an integral part to change the production context.

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