# Direct Metal Laser Sintering: An Overview

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## 1 Introduction

Additive manufacturing (AM) is defined by the American Society of Testing and Materials (ASTM) as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing, methodologies, such as traditional machining”[1]. AM methods differ from subtractive methods, such as milling or turning, by the intuitive concept that the part is being created by the incremental addition of material rather than the incremental subtraction of material[1]. Common industry names for the AM methods are: freeform fabrication, additive processes, layered manufacturing (LM), additive techniques, and additive layer manufacturing (ALM)[1]. Currently, there are seven ALM processes with the following normalized names adopted by ASTM International Committee F42 on Additive Manufacturing Technologies: Vat Photopolymerization process (commercially known as steriolithography), Material Jetting (ink jet printing), Binder Jetting (3d printing), Material Extrusion (fused deposition modeling), Sheet Lamination (laminated object manufacturing), Direct Energy Deposition (laser engineered net shaping), and Powder Bed Fusion [selective laser sintering (SLS), selective laser melting (SLM) , electron beam melting (EBM), direct metal manufacturing, and direct metal laser sintering (DMLS)][1].

Over the last several years, many authors have formed publications aimed at providing an overview of additive manufacturing technologies[2], their respective histories [3,4], and, more recently, a framework for their implementation[5]. Levy provided an excellent summary of LM technologies, their acronyms, and their corresponding development years (Table 1, Appendix A)[2]. In addition, Levy distinguished rapid manufacturing from rapid tooling (Figure 1, Appendix A), and also direct technologies from indirect technologies (Table 2, Appendix A). Bourell provided an “Early Chronology of Additive Processes”and was able to identify the earliest roots of AM technologies from a review of US patent literature[3] (Figure 2, Appendix A), while Shellabear gave “Development History and State of the Art” of DMLS [4]. In 2013, Mellor proposed a framework of AM implementation that consisted of AM: strategy, supply chain, systems of operations, organizational change, and technologies (Figure 3, Appendix A)[5].

The aim of this work is to provide the reader with an understanding of Direct Metal Laser Sintering (DMLS), a specific AM method, by surveying the current literature available on the subject. As mentioned earlier, DMLS would fall under the ASTM standardized name of Powder Bed Fusion. DMLS involves selectively applying energy to a powder bed of metal particles via a laser beam as a means of sintering them together in a layer-by-layer fashion, resulting in a solid part[2]. Mellor provided a very extensive list of benefits associated with DMLS such as the ability to produce parts with complex geometry, save time for creating functional prototypes, and reduce material waste associated with making parts[5].

## 2 History

According to Bourell, all AM methods can be traced back to two early roots, specifically the topographical and photosculpture methods[3]. Blanther developed the topographical method in 1890 as a means to create a mold for topographical relief maps (Figure 4, Appendix A) [3]. The photosculpture method, also created in the nineteenth century, was used as a means to copy objects in three dimensions. Sculpture subjects were photographed using a strategic method which allowed an artisan to create a scale model of the subject in an incremental fashion (Figure 5, Appendix A) [3].

It was not until the 1970's that the first powder AM methods began to appear[4]. In 1971, Ciraud applied for a patent on a powder AM method, which was described in the patent as "the invention makes possible the manufacture of parts which can have extremely complex shapes, without the need for casting moulds"[4]. In the latter half of the 1970s, Householder patented the first powder laser sintering system[4]. This sintering system was described in the patent as able "to provide a new and unique molding process for forming three-dimensional articles in layers and which process may be controlled by modern technology such as computers"[4]. In 1992 and 1994, the first and second commercial selective laser sintering machines were shipped: the Sinterstation 2000 by DTM Corporation and EOSINT (P) 350 by EOS Firm respectively [4]. In 1995, one of the first direct metal laser sintering machines, the EOSINT M 250, was installed for commercial use[4]. This machine allowed for the best part complexity, geometry, and surface quality to date for any direct metal laser sintering machine[4]. In 2004, the EOSINT M 270 machine series was released, featuring a solid-state fiber laser[4]. EOS continued to develop new and exotic models of DMLS machines, even making a precious metal machine (PRECIOUS M 080)[6]. In 2013, EOS released it latest and most advanced machine (EOS M 290) for the manufacturing of high performance metal components[6].

## 3 Definitions

In current literature, DMLS is defined differently by various publication authors [2,4,7,8,9]. Levy distinguished multiple metal AM methods and their processing conditions (Table 3, Appendix A)[2], and his definition of DMLS is most appropriate for the focus of this work. Levy defined DMLS as a single stage part building based on a liquid phase sintering (LPS) process[2]. This definition distinguishes DMLS from two similar SLS methods that produce a solid metal part, which are often mistaken for DMLS. The first method differs from DMLS in that a metal part is created by laser sintering a powdered material containing the desired metal particles, which are covered in a low melting point polymer (commonly called a "binder"), to form what is known as a "green part"[10]. In this indirect method, only the binder is melted, which requires the use of post processing and heat treatment(usually conventional sintering in an industrial furnace) to create the final part[10]. Similarly, the second method differs from DMLS in that a mixture of metal powders is used[10]. One metal powder has a lower melting temperature than the other, which allows for selective melting of one metal, but commonly results in poor mechanical properties of the final part[10].

## 4 Mechanics

In order to understand the basic mechanics of DMLS, one must investigate the following elements of DMLS: binding mechanisms[12], parameters and their relationship to densification[13], processing steps[14], and equipment[14].

### 4.1 Binding Mechanisms

According to the Metal Handbook, "sintering is a thermally activated process (with or without external pressure application), whereby the powder particles are made to bond together, changing physical and mechanical properties, and developing toward a state of maximum density, i.e. zero porosity, by occurrence of atomic transport"[11]. Sintering is crucial to the DMLS process, and is governed by the following parameters: temperature, time, geometry of powdered particles, composition of the powder mix, density of the powder compact, and composition of the protective atmosphere in the sintering furnace[11].

Kruth found that SLS technologies can be categorized by four binding mechanisms: solid state sintering, chemically induced binding, liquid phase sintering partial melting, and full melting (Figure 6, Appendix A) [12]. As mentioned earlier, Levy's definition of DMLS was chosen for the focus of this study, and consequently only the LP partial melting binding mechanism will be discussed in detail[12]. LPS itself has "two technologies" distinguished by the type of binder used, namely that with a different binder, and that with no distinct binder[12]. DMLS would be classified under the latter technology as a fusing powder mixture process[12]. Fusing powder mixtures are characterized by multiple phases that are partially molten[12]. The author would encourage the reader to further examine the literature for detailed information on any of the other binding mechanisms[12].

## 4.2 Parameters and Densification

Simchi provided a comprehensive study wherein six different metal powders were sintered and analyzed to better understand the mechanisms of densification and the role of manufacturing parameters[13].

Process parameters were defined as variables that control the laser sintering process, in contrast to material parameters, defined as: chemical constitutions and the purity of the material, method of alloying, and particle characteristics[13]. Multiple parameters affect the final part density achieved using DMLS, and the corresponding microstructural features. Laser power, laser wavelength, laser spot size, laser scan rate, scan line spacing, powder layer thickness, scanning geometry, working atmosphere, and powder bed temperature are pertinent process parameters. In contrast, particle size, shape, and distribution are pertinent material parameters[13].

Process parameters were varied, along with scan strategy and sintering atmosphere, and final part densities were recorded(see Table 4,Appendix A)[13] .The conclusions of the study were highly valuable to the continued research and improvement of DMLS, and are summarized as follows[13]: Improved densification occurs with increased laser energy input to the powder until a certain saturation point. Chemistry, shape, and size of metal powder particles affect the densification of DMLS processes. Nitrogen sintering atmosphere yields less densification than argon sintering atmosphere.

Dewidar found that for high-speed steel, part density increased with laser beam power, and decreased with increasing scan speed and space[14]. This makes sense because all three process parameter affect the amount of energy (the power density) delivered to the selected region of the powder bed. These results match further studies, specifically Simchi's study of densification of iron[15], Tang's research on copper-based alloy[16], Kruth's study of lasers and materials[17], and Alkahari's study of consolidation characteristics of ferrous-based metal powder[18]. In addition, Tang found that particle shape(which affects the loose powder density) and binder mix fraction affect the final density of the sintered part[18].

## 4.3 Process Steps

All DMLS parts start as concepts designed in a Computer Aided Design (CAD) software[19]. The corresponding CAD file is then be exported in a printable form (.STL, .STEP) to the DMLS machine[19]. The DMLS machine then builds each layer as follows[19]: The stage containing the metal powder is raised. The new layer of powder is spread across the old layer of powder via a spreading mechanism. The laser scans the powder bed to selectively sinter particles according to the current slice instructions dictated by the cad file. The build stage is lowered one layer thickness in preparation for receiving the fresh layer of powder. This process is repeated until the part is finished.

## 4.4 Equipment

Though there are multiple DMLS machines on the market, a DMLS machine generally consists of the following components[14]: a laser for selective irradiation of the metal powder, focusing optics for beam consolidation and maximum intensity of the laser beam, scanning mirrors to direct the beam to the desired powder bed location, a laser chiller unit for temperature control of the laser components, a motion control table for adding layers of material to the powder bed, a build cylinder for adding the new powder layer, a spreader assembly for spreading and leveling the powder layer, an inert gas containment and delivery system for atmospheric gas control which prevents oxidation of particles, and finally a vacuum assembly for flushing the build chamber(Figure 7, Appendix A).

### 4.4.1 Lasers

There are mainly four kinds of lasers that are used in DMLS: Solid Fiber Lasers, Carbon Dioxide (CO2) lasers, Neodymium-Doped Yttrium Aluminium garnet (Nd:YAG) lasers, and disk lasers[4] . The Nd:YAG laser has a wavelength of 1.06µm[4,20]. The CO2 laser was the most common laser used in commercial applications(including DMLS) with a wavelength of 10.6µm; however, it is now being replaced by fiber and disk lasers, which have shorter wavelengths(less than 2 µm), and allow for faster build times[4]. Selection of the laser type and wavelength should be based on the known absorption characteristics of the material (Figure 8, Appendix A) [20].

# 5 Research Areas

Much research has taken place in DMLS since the mid 1990's, most likely being attributed to the release of the first commercial SLS machines[4]. The related works have covered a wide range of subjects involving DMLS, and can mainly be categorized into five topics: effects of DMLS parameters on outputs[13], specific DMLS applications and feasibility[21,22], DMLS simulation and modeling[23], investigation of equipment and process improvements to current DMLS systems[18,24], and DMLS behavior of specific types of powders[10,15,16,25]. For the purpose of this work, certain contemporary investigations have been considered most beneficial to DMLS theory and have been summarized. These summaries only represent a small portion of the breadth of works that have occurred in DMLS, and the author would encourage the reader to delve further into the literature contained in the reference section for more information.

## 5.1 Top Surface Quality

Yang investigated and defined top surface quality (TSQ) as the surface morphology contained in the xy plane (the surface parallel to the substrate) [8]. TSQ is important because every layer of powder is sintered on a previously sintered layer of powder, except for the substrate[8]. If the quality of the bonding between layers is not high, certain defects can occur such as: balling, warpage, poor densification, and oxidation[8]. The study reported that defects could be avoided by maintaining top surface flatness, compactness, and cleanliness (Table 5, Appendix A) [8]. Even further, the TSQ influencing factors were: surface status of the substrate, additive materials, structural powder morphology, scanning space, layer thickness, layer number, and balance of laser power and scanning speed[8]. The results verified that TSQ heavily influences overall final part qualities, and that its control is paramount for the output of high performance DMLS parts[8].

## 5.2 Consolidation Characteristics

Another important publication reported on the consolidation characteristics of ferrous-based metal powder. It utilized a high speed camera with a telescoping lens to record sintering behavior in the powder fusion zone (PFZ) [18]. Line consolidation was a term used to describe the consolidation of metal powders in the PFZ of a laser beam[18]. The line consolidation region was reported to have five distinct areas: the laser beam irradiated area, the PFZ, the liquid/melt pool area, the solidification area, and finally the powder free area (Figure 9, Appendix A) [18]. In addition, it was found that there are five types of line consolidation in DMLS of ferrous based powder, namely: continuous, discontinuous, ball-shaped, weak, and very little consolidation[18]. Poor consolidation will lead to a part with inferior mechanical properties because it will cause inhomogeneity in the three dimensional object's structure[18]. As seen in the Figure 9, continuous consolidation is achieved by carefully balancing scan speed and laser power[18].

### 5.3 Post Processing DMLS Parts

As mentioned earlier, DMLS is based on a LPS partial melting binding mechanism. Because of this binding mechanism, surface roughness, porosity, residual stresses, and microstructural inhomogeneity exist in DMLS parts[9]. It has been widely known that shot peening and other post processing treatments can alleviate the previously mentioned items, and multiple works have been carried out to see how post processing affects DMLS parts [2]. Likewise, the focus of this study[9] was the characterization of post processed samples created from three different DMLS powders. Samples were processed according to Table 6 in Appendix A[9]. The resulting hardness and porosity, cross sectional micrographs, and surface residual stresses were recorded[9]. Analysis of the results led to the following conclusions: DMLS parts without post treatment have the above mentioned inconsistencies, parts that received shot peening showed homogenized surface residual stresses, and aging thermal treatment led to increased material hardness[9].

## 6 Applications

Rapid tooling and rapid prototyping were the main commercial applications for DMLS in its initial years in the market[2,4]. There is a strong and growing interest in what is known as "rapid manufacturing", which is the use of DMLS to create end-use parts[2,4]. Multiple industries are using DMLS for the previously mentioned application because of the benefits of the technology such as material cost savings and low production run capability. The aerospace industry utilizes DMLS to fabricate end use parts(landing gears and titanium components) because of the very high cost savings in comparison with traditional manufacturing methods[5]. In the auto-industry, DMLS is used to create custom high performance metal parts (for formula one)[5]. One such example was the use of DMLS for fabrication of a race car gear box which weighed 30% less than a traditionally manufactured gearbox[5]. In the medical field, titanium alloy dental implants are now being manufactured via DMLS due to the economic advantage over traditional manufacturing[27]. Likewise, bone reconstruction surgeons utilize DMLS to create implants such as craniofacial or orthopedic implants [22].

## 7 Current Barriers and Future Research Areas

DMLS is considered an advanced manufacturing method and is being adopted by a wide range of industries that need any single use or combination of uses for rapid tooling, rapid manufacturing, and rapid prototyping. The survey of the literature on the subject has led the author to conclude that there are five areas that future research will focus on: DMLS process mappings (including parameters) for different powders, equipment and process modifications for increased efficiency(in terms of productivity and economy), application feasibility investigations, simulation and modeling, and sintered part surface quality. Current barriers for DMLS include equipment cost, sintered part surface quality, and build time[2]. As with any relatively new technology, cost is very high in comparison to when it becomes main stream. It will definitely come down as DMLS usage increases.

## 8 Conclusions

It is clear that DMLS has made significant progress since its early roots in the nineteenth century. The rise of DMLS really followed closely with other AM technologies like steriolithography, fused deposition modeling, and SLS. AM became the focus of multiple publications in the 1980s thru the 2000s, when various AM technology publications were being released. The publications increased significantly with the release of the first commercial SLS machines. The past thirty years of publications tended to focus on the effects of DMLS parameters on outputs, specific DMLS applications and feasibility, DMLS simulation and modeling, and investigation of equipment and process improvements to current DMLS systems, and DMLS behavior of specific types of powders.

In surveying the literature, it was found that DMLS process and material parameters strongly influence part densification. In general, the greater the power density can be delivered to the powder bed, the better densification the resulting part will have. Power density can be increased by increasing the laser power, slowing the scan speed, or decreasing the line spacing. Also, smaller particles with clean surfaces are beneficial to densification in DMLS. In addition, post processing techniques such as heat treatment, surface polishing, and shot peening improve DMLS part mechanical properties, and can alleviate inconsistencies that cause inhomogeneity.

Even though the technology is expensive, it is quickly gaining popularity across multiple industries that are benefiting from it as a rapid manufacturing solution. It is also being used for rapid tooling solutions to create complicated injection molding tooling that previously couldn't be created. Businesses that can afford the technology see a drastic impact to their bottom line in the form of material/labor savings, or higher margins on sales due to being able to manufacture parts that were once deemed "impossible". The future literature on the topic will encompass solutions to current barriers like surface porosity and build time.

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# Appendix A

| Name | Acronym | Development years |
|---|---|---|
| **Stereolithography** | SLA | 1986 - 1988 |
| **Solid Ground Curing** († = year of disappearance) | SGC | 1986 – 1988 1999† |
| **Laminated Object Manufacturing** | LOM | 1985 - 1991 |
| **Fused Deposition Modelling** | FDM | 1988 - 1991 |
| **Selective Laser Sintering** | SLS | 1987 - 1992 |
| **3D Printing** (Drop on Bed) | 3DP | 1985 - 1997 |

**Table 1-LM technologies and their corresponding development years[2]**

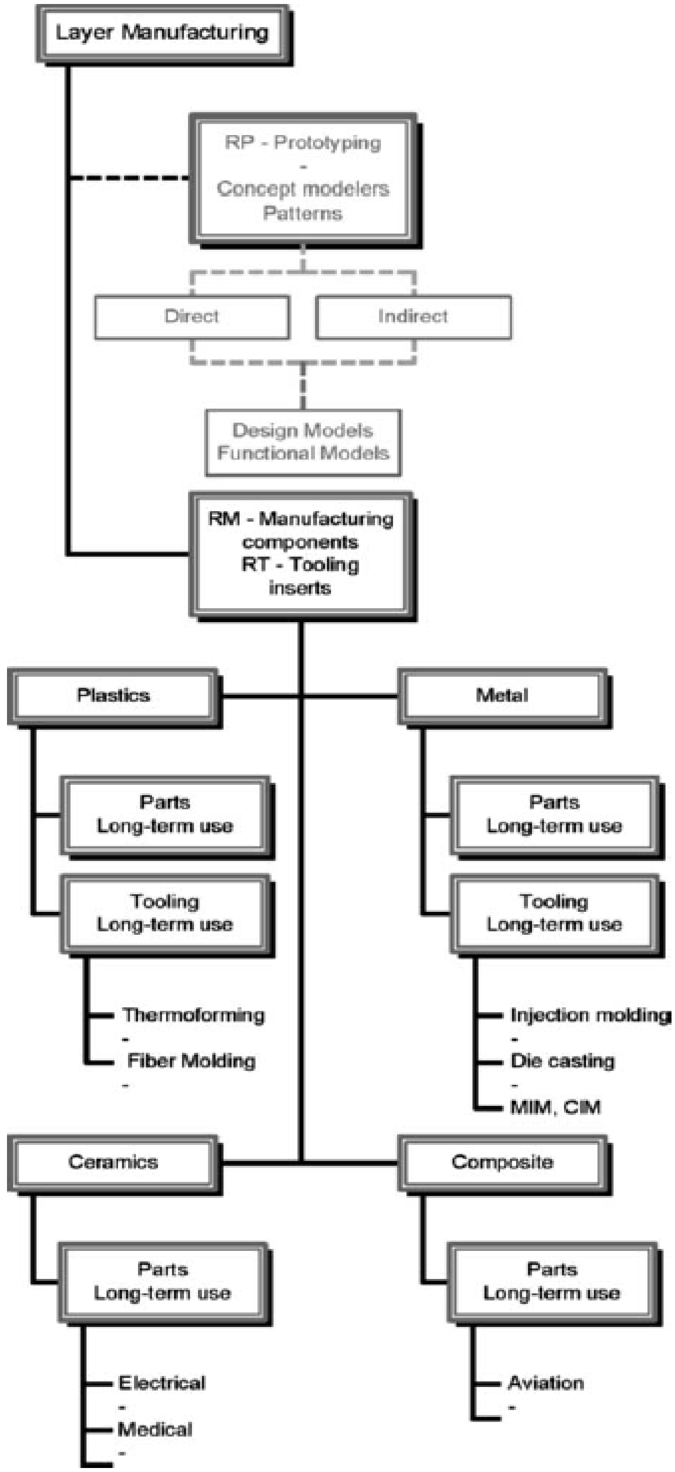



**Figure 1-Layer manufacturing categories chart[2]**

| Material | Direct technologies | Indirect technologies |
|---|---|---|
| **Polymer** | Bridge Tooling, CuPA-SLS (3D-Systems) SLS/SLA soft shells | Silicon rubber pattern RTV Swift™ Tooling (SWIFT™ Tech.) |
| **Metal** | DMLS™ (EOS) Rapid Steel 2 LaserForm (3D-Systems) 3D Printing (ProMetal™) | KelTool™ (3D-Systems) Cast tools Metal spraying (HEK) Metal deposition |

**Table 2- Direct versus indirect technologies table for different materials[2]**

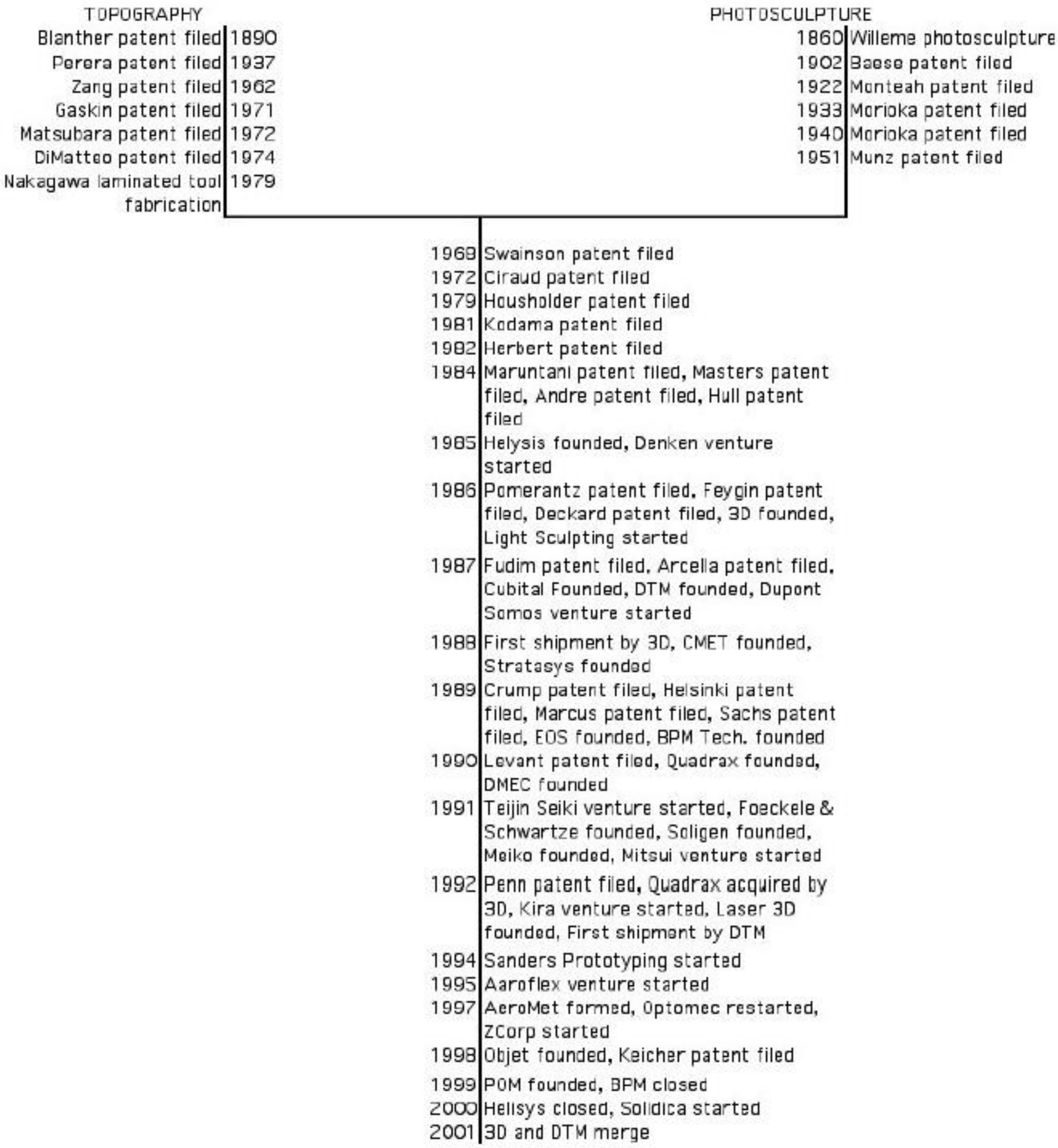



**Figure 2-Timeline showing AM technologies[3]**

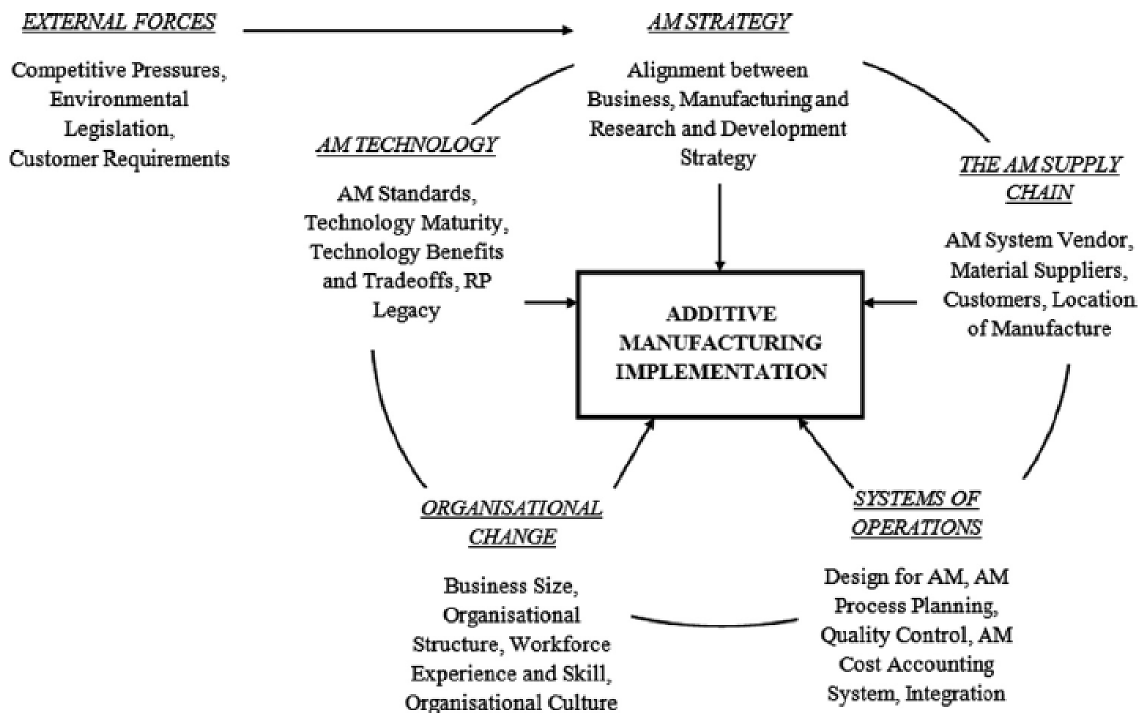



**Figure 3-AM implementation frame work diagram[5]**

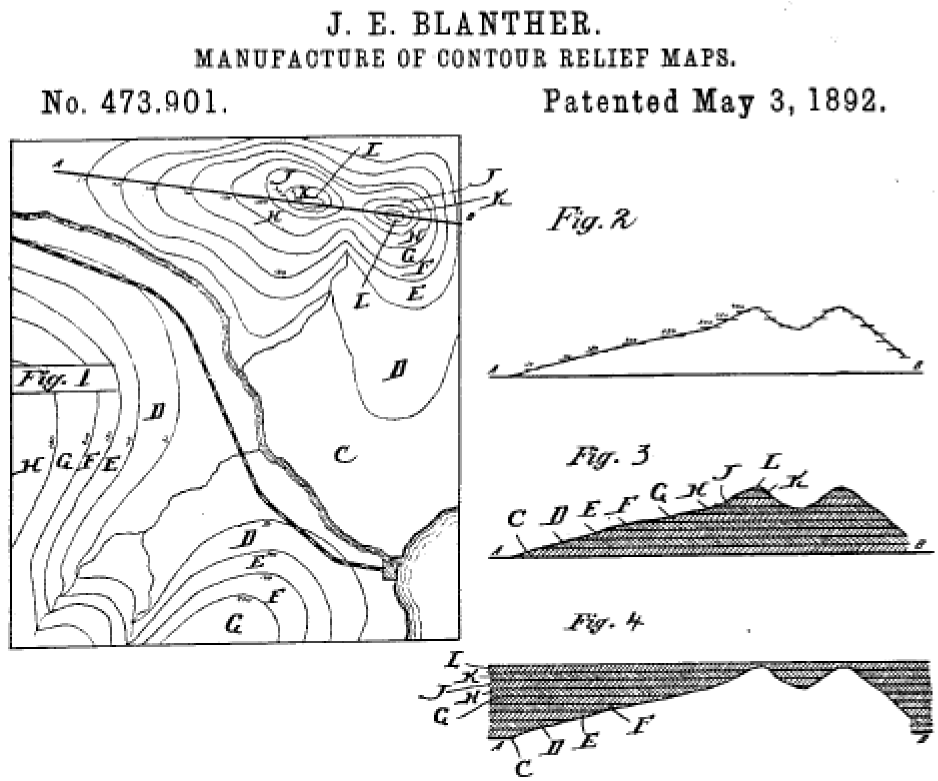



**Figure 4-Blanthers topographical relief method patent[3]**


**Figure 5-Photosculpture method in process[3]**

| *Process* | SLS | SLS | 3DP | SLM |
| --- | --- | --- | --- | --- |
| | ***I stage:*** | ***II stages:*** | ***III stages:*** | ***Melting:*** |
| I | Liquid phase sintering | Polymer binder sintering | Printing | Laser metal melting |
| II | | Debinding + Thermal sintering + Infiltration | Debinding + Thermal sintering | |
| III | | | Infiltratio n | |
| **Laser power** | 200 W | 20 W | No laser | 300-500 W |
| **Laser Type** | $CO_2$ Nd:YAG | $CO_2$ | | Nd:YAG |
| **EOS DMLS** | | | | |
| **3D systems** | | | | |
| **ProMetal** | | | | |
| **F&S, Trumpf, Concept** | | | | |

**Table 3-Different metal AM methods and their processing conditions[2]**

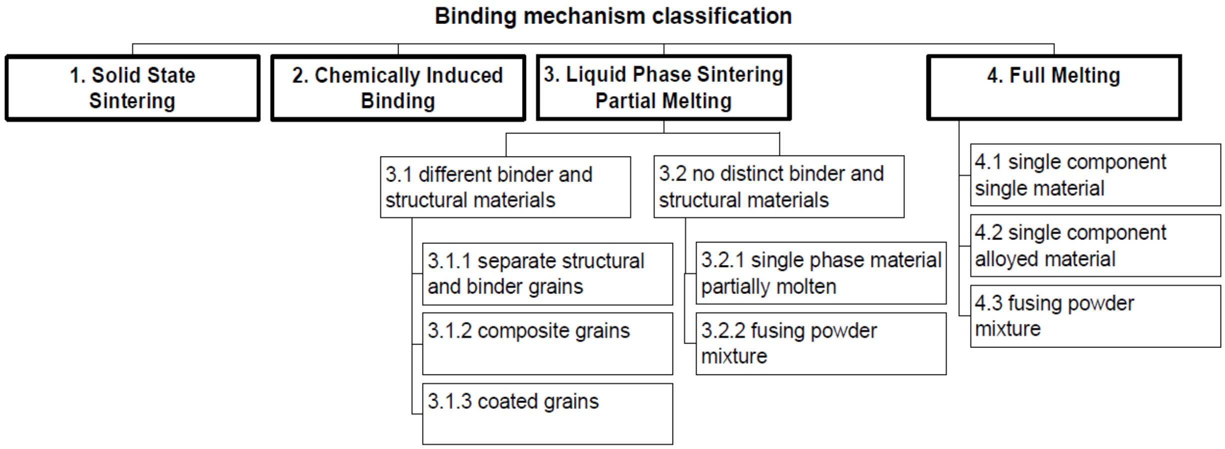



**Figure 6-SLS methods categorized by binding mechanism[12]**

| Material | Laser power (W) | Scan rate (mm $s^{-1}$) | Layer thickness (mm) | Line spacing (mm) | Fractional density (%) |
|---|---|---|---|---|---|
| Fe | 215 | 75 | 0.1 | 0.1 | 73.8 |
| | 192 | 75 | 0.1 | 0.1 | 73.8 |
| | 215 | 75 | 0.1 | 0.3 | 72.0 |
| | 192 | 75 | 0.1 | 0.3 | 71.0 |
| | 180 | 75 | 0.1 | 0.3 | 69.7 |
| | 162 | 75 | 0.1 | 0.3 | 68.5 |
| | 144 | 75 | 0.1 | 0.3 | 68.0 |
| | 125 | 75 | 0.1 | 0.3 | 67.4 |
| Fe–0.8C | 215 | 75 | 0.1 | 0.3 | 76.5 |
| | 192 | 75 | 0.1 | 0.3 | 75.0 |
| | 180 | 75 | 0.1 | 0.3 | 74.5 |
| | 162 | 75 | 0.1 | 0.3 | 73.1 |
| | 144 | 75 | 0.1 | 0.3 | 71.8 |
| | 125 | 75 | 0.1 | 0.3 | 70.0 |
| | 100 | 75 | 0.1 | 0.3 | 66.9 |
| | 215 | 50 | 0.1 | 0.3 | 78.1 |
| | 215 | 100 | 0.1 | 0.3 | 72.2 |
| | 215 | 125 | 0.1 | 0.3 | 71.4 |
| | 215 | 150 | 0.1 | 0.3 | 67.8 |
| | 215 | 200 | 0.1 | 0.3 | 64.2 |
| | 215 | 250 | 0.1 | 0.3 | 60.5 |
| Fe–4Cu | 215 | 75 | 0.1 | 0.3 | 74.9 |
| | 180 | 75 | 0.1 | 0.3 | 73.8 |
| | 144 | 75 | 0.1 | 0.3 | 70.7 |
| | 100 | 75 | 0.1 | 0.3 | 56.6 |
| Fe–0.8C–4Cu–0.4P | 215 | 75 | 0.1 | 0.3 | 80.6 |
| | 180 | 75 | 0.1 | 0.3 | 78.0 |
| | 144 | 75 | 0.1 | 0.3 | 75.0 |
| | 100 | 75 | 0.1 | 0.3 | 67.7 |
| | 166 | 300 | 0.1 | 0.3 | 59.0 |
| | 166 | 400 | 0.1 | 0.3 | 54.1 |
| | 166 | 500 | 0.1 | 0.3 | 51.3 |
| | 166 | 600 | 0.1 | 0.3 | 49.4 |
| 316L | 215 | 50 | 0.05 | 0.3 | 93.6 |
| | 215 | 100 | 0.05 | 0.3 | 86.9 |
| M2 | 200 | 50 | 0.1 | 0.3 | 88.2 |
| | 200 | 75 | 0.1 | 0.3 | 85.8 |
| | 200 | 100 | 0.1 | 0.3 | 84.5 |
| | 200 | 125 | 0.1 | 0.3 | 79.2 |
| | 200 | 150 | 0.1 | 0.3 | 76.6 |
| | 200 | 175 | 0.1 | 0.3 | 62.1 |

**Table 4-Densification of metal powders[13]**

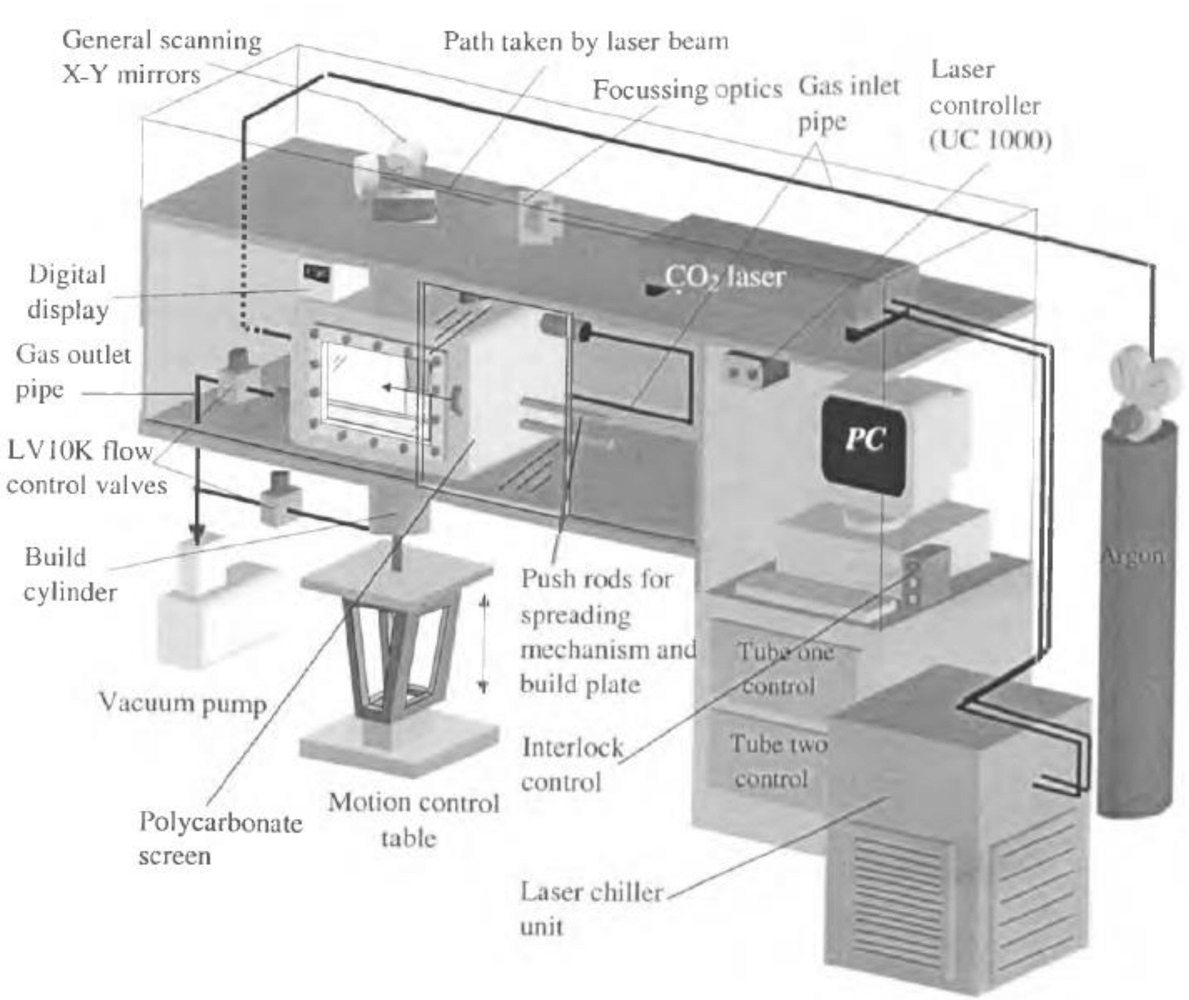



**Figure 7-DMLS equipment layout[14]**

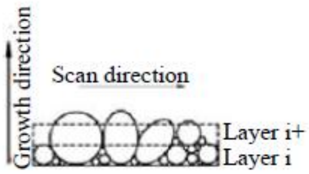
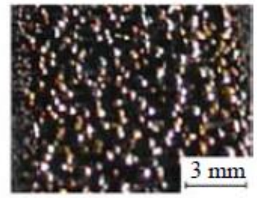
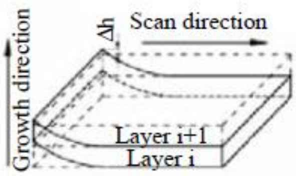
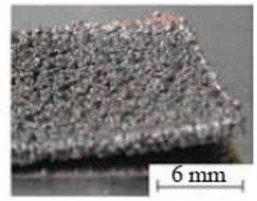
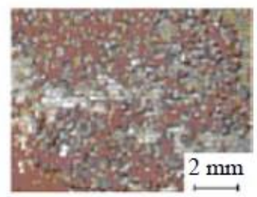
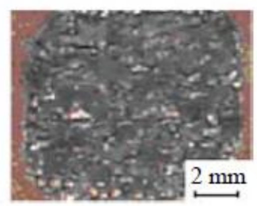
| Type | Term | Description | Schematic | As-DMLFed photo |
|---|---|---|---|---|
| Flatness | Balling | There are a large number of sphere particles with different diameter in the current layer, and the height of maximal particles exceeds the layer thickness |   |   |
| | Warpage | The solidified part curls seriously, which appears more easily in the edge or corner. When deformation exceeds layer thickness, DMLF process will be forced to terminate |   |   |
| Compactness | Bad densification | It seems that the flatness of top surface is very good. However, metal powders are very slightly melted and arrayed with poor bonding strength |   |   |
| Cleanliness | Oxidation | Local or entire oxidized area with black color exists in laser scanned area, which reduces seriously the stability of process and strength of metal parts |   |   |

**Table 5-Surface defects TSQ[8]**

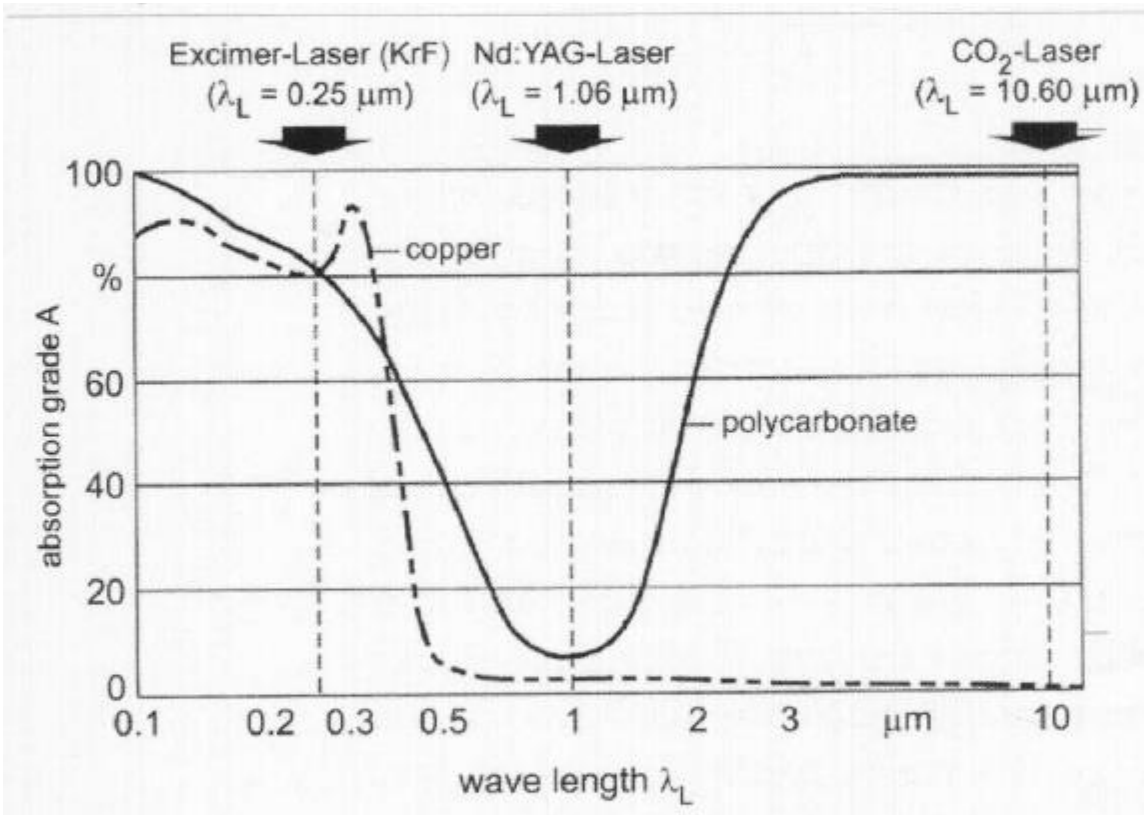



**Figure 8-Absorption of copper and polycarbonate with different laser wavelengths[20]**

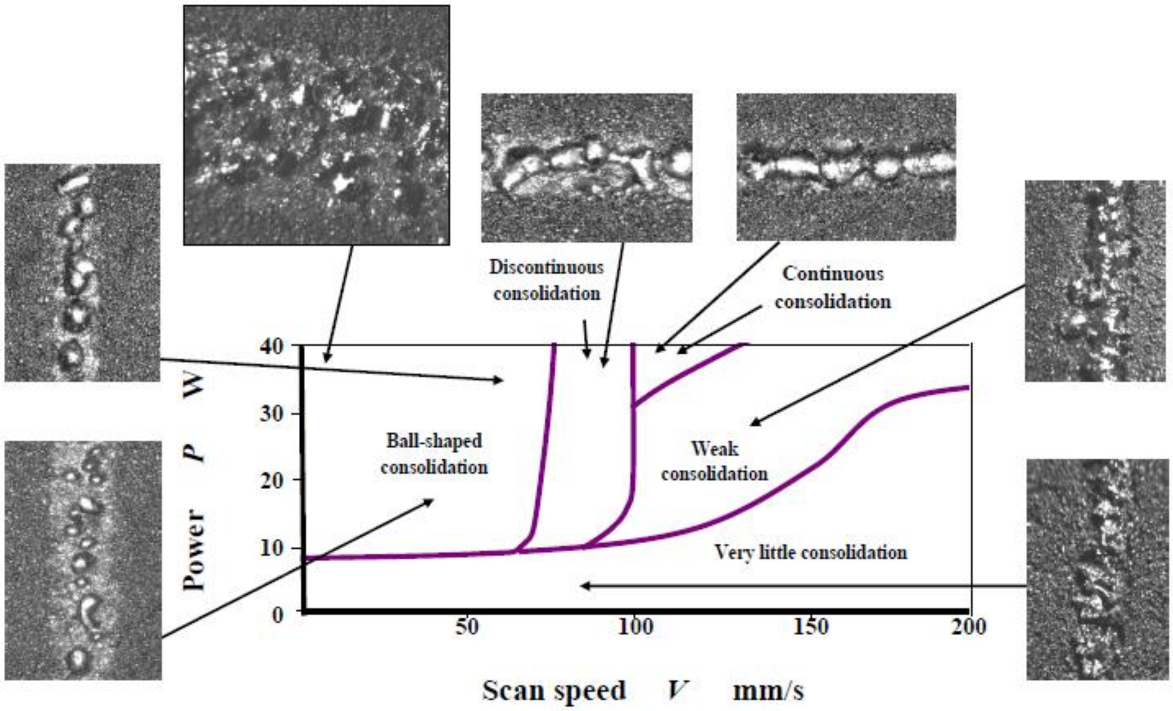



**Figure 9-Consolidation mapping with sample photos[18]**

| Sample | Material | Heat treatment | Shot peening | Hardness HV 10 | Porosity % |
|---|---|---|---|---|---|
| H1 | Maraging Steel | No | No | 363 ± 5 | 0.24 |
| H2 | Maraging Steel | No | Yes | 363 ± 5 | 0.28 |
| H3 | Inconel 718 | No | No | 319 ± 18 | 0.02 |
| H6 | Inconel 718 | Yes (Aging) | Yes | 470 ± 8 | 0.17 |
| H7 | CoCr alloy | No | No | 406 ± 7 | 0.06 |
| H8 | CoCr alloy | No | Yes | 413 ± 7 | 0.04 |
| H10 | CoCr alloy | 2 h at 650 °C in $N_2$ | Yes | 453 ± 7 | 0.05 |
| H12 | CoCr alloy | 2 h at 850 °C in $N_2$ | Yes | 510 ± 8 | 0.02 |
| H13 | CoCr alloy | 2 h at 850 °C in air | No | 503 ± 13 | 0.06 |
| H14 | CoCr alloy | 2 h at 850 °C in air | Yes | 506 ± 8 | 0.13 |
| H16 | CoCr alloy | 2 h at 1000 °C in $N_2$ | Yes | 509 ± 23 | 0.04 |
| H18 | CoCr alloy | 2 h at 1000 °C in vacuum | Yes | 420 ± 6 | 0.03 |

**Table 6-Sample processing information[9]**