Rapid Manufacturing and Rapid Tooling with Layer Manufacturing (LM) Technologies, State of the Art and Future Perspectives

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Abstract

Additive processes, which generate parts in a layered way, have more than 15 years of history. These processes are not exclusively used for prototyping any longer. New opportunities and applications in appropriate manufacturing tasks open up, even though the economical impact is still modest.

This review starts with the definition of Rapid Manufacturing and Rapid Tooling, dealing only with direct fabrication methods of components. A systematic material dependent classification of layer manufacturing and process oriented metal part manufacturing techniques are proposed. The generic and the major specific process characteristics and materials are described, mainly for metallic parts, polymer parts and tooling. Examples and applications are cited.

The paper attempts to understand the state of the art and the prospective, to put questions, to understand limits, to show opportunities and to draw conclusions based on the state of the art.

Keywords

Rapid, Manufacturing, Tooling

1 INTRODUCTION

Additive processes, which generate parts in a layered way, have 15 years of history (CIRP keynote 1991) [56]. It started in the late 80's with Stereolithography. Since then, many new ideas have come up, many patents have been deposited, new processes were invented and commercialised, some of which have already disappeared. An overview is given in Table 1.

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, acronyms and development years [12].

LM (Layer Manufacturing) technologies are also often referred to as RP (Rapid Prototyping) technologies. A universally agreed terminology does not exist at this point. Some inconsistencies and doubts can be overcome by using the SME published dictionary [94].

It is well known that the introduction of a new manufacturing technology often begins in the field between scientific push and industrial pull. These

acceptances evolve usually within a period of 6-10 years and last a further 5-8 years in anticipation of entering in production. After a pioneering and pure research ("PhD") stage we experience an oversell, a disillusion and finally an acceptance: see Figure 1 [128]. This was confirmed at the introduction of EDM, W-EDM, HSC and Laser Cutting. Water Jet Cutting (WJC) is now in its acceptance phase. In the case of LM processes the need is clearly confirmed by the market! We are in the disillusionment stage.

Figure 1. The scientific push and industrial pull in technological evolution.

The situation is also confirmed by the revenue development in this segment (Figure 2) and is presented yearly by Wohlers Association inc. in the book "The state of the Industry" [130].

We are still far below the one billion \$ sales. The market volume is steadily increasing but the systems sales show stagnation (Figure 2). This is raising the question of significance and future relevance. Will a significant breakthrough occur?

Compared to machine tool revenues in other manufacturing sectors the question is even more evident. Take e.g. the EDM market (equipment only) with 1,5–2 billion \$ yearly, it is 5-8 times the RP equipment sales value.

“Time to Market” was originally the strongest inspiration and economical driving force in RP. Product life cycle becomes shorter and builds up interest [68]. Virtual modelling largely fulfils these needs and is in continuous rivalry with RP. This conflict on the other hand increases the interest and chances of RP processes as alternative or autonomous manufacturing processes and augments the interest. The production of long-term usable components and tooling increases the interest in Layer Manufacturing.

The following will attempt to understand the state of the art and the prospective, to put questions, to understand limits, to show chances and to draw conclusions based on the state of the art.

Figure 2. Development of Revenue of RP equipment sales (clear) and services (clear).
Source: Wohlers Associates Inc.

2 DEFINITION AND CLASSIFICATION OF RAPID MANUFACTURING

The major players in this field have already come to the conclusion that a breakthrough can only happen on the basis of manufacturing applying the RP technologies on a large scale. New terms were created or considered: terms like mass customisation (MC) by Siemens and Phonak [80], Production on Demand (POD) by Boeing, and recently Advanced Digital Manufacturing (AMD) by 3D Systems.

What is Rapid Manufacturing (RM)?

Rudgley M. defines RM as “the manufacture of end-use products using additive manufacturing techniques (solid imaging)” [106]. RM must guarantee long-term consistent component use for the entire product life cycle or for a defined minimal period for wearing parts. This calls for a most significant role of materials in the LM technologies as argued later.

For long-term consistency, the parts or tools can be made out of four main basic material families fulfilling the required physical, mechanical and

geometrical properties (Figure 3). In our definition we consider only **direct component production**, meaning that the final component is generated directly from a geometry file, at least in a near net shape quality. The indirect production via patterns and reproduction, by e.g. casting, are not considered as LM, even though generative processes have a significant ability and importance representing an important option in those process chains.

Figure 3. Material dependent Layer Manufacturing - LM structure.

Further, we exclude the Rapid Prototyping issue. It seems that the same processes have found their well defined and justified position in the Rapid Product Development cycle [69] as confirmed by

Bernard A. and Fischer A. [13] and Levy G. [73] for instance.

3 DEFINITION AND CLASSIFICATION OF RAPID TOOLING

Today a great demand exists on RPT-technologies to support product development by tooling or tooling inserts that allow the production of larger series and at the same time enables the production of those parts in materials and with technologies similar to the ones used later for series production runs. The most notable advantage is the integration of production planning and testing within the product development period [38].

What is Rapid Tooling (RT)?

In contrast to the previous definition of Rapid Manufacturing (RM), Rapid Tooling (RT) aims only at long-term consistency tools, meaning a tool able to form several thousands or even millions of parts before final wearing-out.

Referring to tooling, mainly plastic injection moulds are considered, as these are the most frequently used forming tools. Naturally we have to consider as well other needs with greater difficulty as in die casting, sheet metal forming and forging dies [6] [9] [86] [87] [89]. Those applications increase substantially the requirements on thermal and mechanical load and wear. On the other hand we have also to consider tooling with lower load that is also of great interest: for example for thermoforming, fibre forming and similar processes [29] [77].

So, development and research was initiated for a wide variety of processes [24] [61] [70] [71] [75] [97]. They may be grouped in four categories: Direct and Indirect (indirect means using a part model) procedures and according to the material type in metal or polymer materials [23]. Table 2 gives some examples of such processes.

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. Process chains options for mould manufacturing.

The rapid tooling options have to be selected in accordance with the final component material and the requested quantity: see Figure 4. We see clearly that for technically upper end plastics and higher quantities a more sophisticated tooling option has to be selected [123].

A recent DELPHI forecast on Rapid Tooling (RT) use indicated that the well-established quality hardened alloy steel tools are preferred: Figure 5

In the following, we will consider only **the direct methods** and applications having chances to fulfil a serial production demand in terms of quantity and quality.

Figure 4. Relations between cast material quantity of parts and selected RT technique.

Figure 5. Rapid Tooling classification and users preferences (Source FHS).

4 THE TECHNOLOGIES INVOLVED

Over the last decade over 30 companies developed and marketed LM machines based on different physical principles and implementation concepts (see Table 1). All have in common that the components are generated layer by layer also known as "Material Increase Manufacturing" [56]. In general they use the same virtual digital data base, i.e. a volume 3D CAD model in one of the commonly used data formats (STL, DXF, IGES, STEP, etc.). Advanced approaches are investigated [25] [55].

The technologies can be divided as Laser and Non-laser supported and structured according to the starting material physical state, under the characteristic of RP technologies [56].

5 THE MULTIDIMENSIONAL PROPERTIES, AN OBSTACLE OR AN OPPORTUNITY?

All LM technologies have some generic and exclusive common features, which convey a number of synergies among them. The main appeal is towards the novel possibilities and applications offered by those technologies. However, those technologies still differ greatly in terms of physical process, geometry and materials that can be processed and performance (production speed, product strength for given material, etc.). Some decision making methodologies were developed to select the proper process for a particular application or part [79]. Before looking into the single RP-processes one by one, we will first review the generic issues of geometry, performance and material.

5.1 Geometry

The geometrical independence and greater liberty seems to be the most attractive feature of RP processes: undercuts, overhangs, free forms, as well as elementary shapes can be easily produced (Figure 6). This high flexibility opens the way to both small lot and in particular mass customisation. The size of the object is process dependent: SLS, SLA and FDM are typically used for medium size whereas very large parts are limited because of performance and economical considerations besides the availability of commercially large equipment. Today, LM of metallic parts by SLS or laser cladding is typically limited to sizes of 200...300 mm. 3D printing has a build size 1000x500x250 mm and big metal parts were successfully produced. SLS of polymer and sand powders is possible on machines with ranges of 700...800 mm. SLA prototypes made from photo-polymer can be built in one piece on machines with a range up to 2200 mm. On the other end of this dimensional-scale LM processes give a chance for complex mini and micro parts [14] [81].

Figure 6. LM complex geometry demonstrated by a medical SLS model made in PA 12 material (left) and a SLM made lightweight part in stainless steel (right) (Source: FHS-RPD, ILT).

The combination of geometrical freedom and mass customisation give an excellent prospect for medical applications (teeth, bones, supports, implants etc.). However the geometrical freedom of some processes is still somewhat restricted by the need to provide and remove support structures underneath the part and within internal cavities or difficulties to remove un-solidified material contained in such part cavities. Some partial solutions to the problem of support structures have been previously reported in a CIRP Keynote 1998 [59].

The almost total liberty in geometrical parts manufacturing opens an interesting application slot between EDM and HSC. The problem of machining deep narrow slots in polymer injection tool inserts can be solved economically as shown in Figure 7. The insert was produced in SLS with integrated conformal cooling and cut with WEDM. Previously sinking-EDM machining of the insert required 2x13 electrodes. A significant time and cost saving was demonstrated. The tooling process chain can be considerably shortened [109].

Figure 7. a) Polymer cover with insert, b) EDM required electrodes (13x 2). c) STL data with cooling, d) SLS sintered inserts (Source: FHS-RPD, BOSCH).

The new possibilities may be enhanced with a modified design paradigm "Design for Layer Manufacturing" (DLM). The first steps in this direction are e.g. the design tools for conformal cooling channels [33].

5.2 RP Process Performance

All processes still have wide deficiencies with respect to accuracy and repeatability which are typically in the range of 0.1 to 0.2 mm for 100 mm. A combination with subsequent traditional machining operations for particular features has to be included (at least for the time being) [45] [76].

The surface finish depends on the layer thickness and varies according to the surface inclination; the orientation in the workspace can also influence the functionality of certain surfaces. A characterization for LM parts is proposed by Leonardo P.M. et al [78] and Campbell [18].

Another issue is the productivity [100]. Immense steps forward were implemented in recent years, as for example the scanning speed of SLS started with 1.5 m/min in 1996 and recently reached 10 m/min with better or equally reliable overall quality. This means a 5 times increase in productivity (Figure 8). An alternative solution is provided by the implemented multi laser beam systems (Figure 9).

Figure 8. Productivity increase due to laser scan speed.

Figure 9. multi beam systems (Source:., AAA⁺ CMET).

5.3 Material

The largest difference between LM processes concerns processable materials. The strong link and the extremely small choice of material towards each process is a major constraint (CIRP Keynote 1998) [59].

Figure 10. Strength of FDM specimens with various raster orientations (and 0.003 mm air gaps) compared with injection moulded ABS P300 (Source: Montero).

The selection of a production process becomes unavoidably a design decision and a constructive design complication [110]. A supplementary matter is the anisotropy of the components according to layer orientation. The variance in the mechanical properties has to be considered. A characteristic illustration to validate FDM ABS material is shown in Figure 10. Montero et. al. used DoE (Designed Experiments) for the ABS P400 material

characterisation. They demonstrate the strong anisotropy behaviour of the parts and propose designer rules applicable only for simple parts [88]. Typical anisotropy values in several layer directions, for SLS PA12 material is given in [80].

6 DIRECT MANUFACTURING OF METAL PARTS

Today, the biggest chances and efforts are placed in the direct manufacture of long-term consistent metal parts [10]. The options are numerous. We can divide the options into two main categories: Non-Melting and Melting processes.

A further substructure reflects the used material form: powder, foils or wire (Figure 11). At the third level we can distinguish between the applied fundamental RP process.

Four basic material forms and 7 different RP principles are competing in direct metal parts fabrication. This requires an accurate validation and trade off for specific applications. However not all processes are equally advanced. Some are only in the very early stages. 18 systems commercially available are listed in Appendix 1.

Figure 11. Four basic material forms and seven different RP principles are competing in the direct metal parts fabrication.(see also App. 1).

The competitive position of LM for metal components relative to alternative manufacturing processes is a function of the geometrical complexity and required quantity. A graphical presentation can be extrapolated from the diagram published in reference [85]: Figure 12. LM is positioned at medium to high geometrically complex parts and at relatively low quantities. The borders are floating and have to be evaluated from case to

case. However, in principle, more productive and better performing LM processes will shift the corresponding upper quantity limit upwards.

Figure 12. Qualitative situation of the LM direct metal components production relative to usual options.

6.1 Non Melting LM Processes

Selective Laser Sintering - SLS

The selective laser sintering process was first described in the US patent 4247508 by Housholder and was evolved by Deckard at the University of Texas (US 4863538). It became the most advanced process used in Rapid Manufacturing for metallic and polymer parts. The research efforts are very broad in many universities and institutions worldwide.

Process	SLS	SLS	3DP	SLM
	<i>I stage:</i>	<i>II stages:</i>	<i>III stages:</i>	<i>Melting:</i>
I	Liquid phase sintering	Polymer binder sintering	Printing	Laser metal melting
II		Debinding + Thermal sintering + Infiltration	Debinding + Thermal sintering + Infiltration	
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. Overview of the metal manufacturing systems.

For the production of metal components with SLS, we distinguish between a single stage part building, based on the liquid phase sintering process (Nyrhilä O. Pat US 5,732,323 prio. 1994) [49] [58] [96] [118] [124], and a two-stage process chain. The two stage material system is using a polymer binder that has to be debinded, after which the metal particles are thermally sintered. In the two stage processes different Micro - Joining mechanisms between the

metal particles can be distinguished (Gatto A., Iuliano L. [30]). The 3D-Printing approach discussed later, is a similar two-stage process with a polymer binding type stage. Selective Laser Melting (SLM) is a metal melting based process described in a patent by Meiners W. [83] (Fraunhofer Gesellschaft) US 6,215,093 (DE 196 49 865 prio. 2.12.1996) and has parallels to the one-stage SLS process. An overview is given in table 3.

Looking at the state of the research and the process models available (Abe, Glardon, Kruth, Katz) it is clear that the Nd:YAG laser (wavelength 1061 nm) is a better choice than CO₂ lasers (wavelength 10.6 µm) due to the better absorption of metals for shorter wavelength, the larger parameter window, smaller spot size and higher specific power for the one-stage SLS and SLM processes [1] [5] [16] [34] [51] [60].

The One-Stage SLS Process

This process (Figure 13), also known under its commercial name Direct Metal Laser Sintering (DMLS™) [48] [52], is practiced with different materials (see table 4). One of the main issues is porosity [117], which still may call for a subsequent infiltration or/and furnace sintering.

Figure 13. The One-stage Liquid sintering is a portion of the practiced thermal sintering with left over porosity.

The material composition, the grain size and post treatment with shot penning have helped to some extent to reduce this problem: Figure 14. The recently introduced 20 µm metal powders brings a significant improvement in mechanical properties surface quality and porosity but the productivity decreases strongly (Figure 15) [114] [115].

Figure 14. SLS DMLS Direct-Metal 50V-2 grain size 50 µm porosity 10-15% , left before right after shot-penning ZX and YX plane(Source EOS).

Figure 15. SLS DMLS Direct-Steel 20V-2 grain size 20 μm porosity ~ 5%, in the ZX plane; left before right after shot-penning (Source IPT).

Figure 16: The 2-stage process chain: a) powder with binder, b)-green part, c) oven cycle, d) full dense part, e) necking between particles - brown (Source: FHS, EMPA).

The Two-Stage SLS Process

In the 2-stage process, laser sintering creates a green part [76]. The metallic metal powder particles are bound together with an organic binder at low temperatures and with a relatively low strength. The final properties are obtained from subsequent thermal sintering (necking) in a high temperature oven cycle followed by infiltration with bronze or copper in the same cycle. The result is a fully dense solid part (Figure 16) [27].

Similar to other RP processes, the accuracy analysis on tools and parts, produced with this process, shows a big scatter and acceptable values only for small parts (Figure 17). It is clearly near net shape manufacture. Big efforts are needed to improve this shortage.

SLS Long-term consistent LM metal materials properties

The choice of a manufacturing process is a technological decision and done in consideration of geometrical shape, quality, quantity, etc. In traditional design, the selection of the manufacturing process and of the component material are almost independent parameters or at least have a very large variation possibility for the designer. On the contrary, in LM the material and process form a dependent non-detachable selection. Thus we automatically select the mechanical properties of the part given for commercial materials in Table 4. An individual characterisation is indispensable [120]. The freedom is in the almost paramount relationship to geometrical shape and complexity.

The selection of LM as a production method is primarily a design and not a manufacturing decision. Thus we automatically select the mechanical properties of the part when selecting the production method.

Figure 17. The accuracy analysis demonstrates the ability to manufacture near net shape parts only (Random measurements done on different geometries and different production batches) (Source. FHSg).

Advanced material systems

During the years, much research work was done and published, and patents were deposited, for advanced SLS metal material systems. Regrettably none have yet reached industrial maturity. The list of tried materials is long:

At IPT Aachen (D), **IN 718**, **ZrSiO₄**, **SiO₂** was experimented [53]. At KUL Leuven (B) **WC-Fe-Ni**, **SiC**, **WC-9Co** and **WC-12Co** cermets were tried out [60][64][65][66]. **Cu**, **Al** and **Ti** were experimented by Osakada and Abe [4]. Bampton C.C., US patent 5,745,834 (prio. 19.09.1995) [11], utilises powder blends containing a base metal, a lower melting temperature metal and a polymer binder. The technology called DMF (Direct Metal Fabrication), was developed at the Rockwell Scientific Centre. They report successful technology use for **mild steel**, **stainless steel**, precipitation hardened **tool steel**, and nickel based **superalloys** and **copper**

		Reference steel: P20											
		Ref. Al 7075 Zn Mg Cu 0.5											
		DTM RapidTool 1											
		DTM RapidSteel 2.0											
		DTM LaserForm ST 100											
		DTM LaserForm ST 200											
		EOS Ni - Bronze Sn60Pb-infiltrated											
		EOS (Electrolux) DMLS DirectMetal™ 100 – V3											
		EOS (Electrolux) DMLS DirectMetal™ 50 – V2											
		EOS (Electrolux) DMLS Directsteel™ 50 – V1											
		EOS (Electrolux) DMLS DirectMetal™ 20 – V2											
		EOS (Electrolux) DMLS Directsteel™ 20 – V1											
Grain size	[μm]	-	-	50	34	23	20	100	100	50	50	20	20
Tensile Strength	MPa	950	570	475	580	510	435	162	199	199	499	450	600
Yield Strength	0.20%	751	502	255	413	305		124	n.a	n.a	n.a	n.a	n.a
Young Modul	GPa	210	65	210	263	137	142	60	n.a	n.a	n.a	n.a	n.a

Table 4. To date commercialised SLS metal powder systems and their mechanical properties.

alloys. The **A6 Tool Steel** announced by 3D Systems might be based on the DMF technology or the II stage SLS process.

According to Stucker B.E., in US Pat. 5,870,663, the material system **ZrB₂/Cu** is used. for the manufacture of low wear EDM electrodes [121].

Very close to practical use is the development of aluminium alloy infiltrated with aluminium by the University of Queensland [113]. A two-step approach was implemented. Aluminium powder with organic polymer binder is selectively laser sintered. In the thermal sintering, magnesium, especially at low concentrations, has a disproportionate effect on sintering because it disrupts the passivating Al₂O₃ layer. Additives as little as 0.07 wt% (100 ppm) lead, tin or indium promotes sintering in an Al-Zn-Mg-Cu alloy. Additionally the oven atmosphere was optimised. The infiltration is done with aluminium alloys [111] [112] [113] (Figure 19). Typical properties of SLS aluminium parts (Figure 18) are given in Table 5.

Shrinkage	%	<1%
Tensile strength	MPa	Up to 200
Ductility	%	Up to 0.5%
Furnace time	H	<24

Table 5. Mechanical properties of SLS made Aluminium parts.

Trials to further improve the quality of SLS mould inserts are undertaken by applying coatings on the SLS inserts. Systematic approach and research is still missing, but the primarily results are encouraging [42].

Despite a large number of patents, research results and success claims, a real breakthrough has not happened. The chances are there. What are causing the success delay? What are the reasons for the hesitating break through? Will SLM (see

§6.2) have quicker immediate success? These are open questions for the near future.

Figure 18. SLS made example of an Aluminium part (Source: 3D Systems).

Some SLS manufacturing examples in metal

Manufacturing metal parts is still limited to complex medium sized tooling inserts, but there is an evolving need and application [21] [47] [49]. It allows the production of inserts with complex parting lines and deep slots. Productivity increases, in injection moulding can be accomplished by incorporating conformal cooling channels [23] [50]. The actual high cost and low productivity of the inserts are the main reasons for the limited application [122].

Three Dimensional Printing - 3DP

E. Sachs and M. Cima from the MIT, the inventors of the 3DP process, have already published a paper on their work in the CIRP annals in 1990 [107]. The process and equipment were optimised for several applications: manufacture of ceramic (casting) shells, metallic parts, wax prototypes, rapid tooling and RM. Figure 21 describes the printing procedure for metal parts.

The process is a two-stage process (table 3) and suitable for large parts as well as small ones (Build volume 1x 0.5x0.25 meter). The multi nozzle 'drop on demand' jet printing concept on a powder bed allows a high productivity with acceptable geometrical precision. Some printing limits, defects

and considerations are discussed by Lanzetta M. and Sachs E. [62] [63].

Figure 19. SLS Aluminium formation steps a) green resin bonded, b) burnout, c) skeleton, d) infiltration (Source: 3D Systems)

Figure 20. SLS two-stage made tooling inserts material LaserForm 100 (Source FHSG)

The material restrictions are mainly induced by the need for a subsequent thermal sintering and infiltration process [46]. In the metallic applications, stainless steel powders serve as basic stock material and a polymer low viscosity acrylic binder is used. The available metal material grades, mechanical properties and performance are given in Table 6, [7] [101].

A tooling example for Lost Foam casting patterns is presented in Figure 22. Tooling to support lost foam casting normally requires machining the mould cavity, and subsequently drilling vent holes. Using 3DP, vent holes of a diameter of .38 mm (0.015”) can be directly incorporated in the mould. 1200 of these holes can be distributed in a one square foot area. This resulted in a 50% reduction of tool delivery time. Ongoing efforts in modelling and material search are reported by I Lembo and Anderson [67].

Figure 21. 3DP basic printing equipment concept and process chain the green parts are thermally sintered and infiltrated in the following steps
Source : Extrudehone-Prometal.

Material grade		S3	S4
Tensile Strength	MPa	406 MPa	683 MPa
Elongation	%	8.00	2.30
Hardness	HB	60 Rockwell B Nominal 107 HBS (3000 kgf)	26 Rockwell C Nominal 258 HB
Surface finish	µm	12.5 µm Typical	12.5 µm Typical
Accuracy	+/- mm	+/- 0.13 mm +/- 0.002 mm/mm	+/- 0.13 mm +/- 0.002 mm/mm
Density of parts	%	94	94
Production rate	mm ³ /ho ur	4.1 x 10 ⁶ mm ³ /hour	4.1 x 10 ⁶ mm ³ /hour

Table 6. 3DP available metal material grades mechanical properties and performance.

Figure 22. Lost Foam Casting: tooling for PSE (expanded polystyrene patterns) (Source : Extrudehone-Prometal).

Paste-based Stereolithography - OPTOFORM

The OPTOFORM process is a variant of the classical Stereolithography process, in which the liquid photopolymer is substituted by much more viscous polymer paste (i.e. an acrylate or epoxy photopolymer with a higher degree of pre-curing). This process, initially developed by a small French company, is now further perfected by the leading US SLA vendor. The major advantage of the process is that it not only allows one to produce plastic

prototypes as in traditional Stereolithography, but the high viscous paste can be filled with large amounts of metal or ceramic powder material without a tendency of sedimentation. For metals, filling rates up to and even over 60% in volume (90% in weight) are possible. Subsequently, debinding and furnace sintering is applied to yield near 100% dense metal or ceramic parts. Special kneading recoating systems and evaporating viscosity modifiers have been introduced to make the use of paste material possible [44]. The process has been demonstrated to be able to produce good quality steel, titanium and ceramic parts (Figure 23).

Figure 23. a) Titanium and b) ceramic part produced by Optoform-SLA (Source: CRIF/KUL).

Laminated Object Manufacturing – LOM

The Laminated Object Manufacturing concept was investigated very early (1984) by Nakagawa T. and Kunieda M. for laminated metal sheet for tooling [92] [93]. The technology has made progress since then. Two advantages are inherent: the process is suitable for medium and large sized parts and secondly it is almost irrelevant what material is used (paper, plastics and metals are often applied). It is hence of considerable interest for car and instrumentation applications.

Figure 24. the principles steps in the LOM process chain.

Figure 24 describes the steps in LOM. Recently, the process was refined taking advantage of progress in laser technology, IT and design optimisations. The adaptive slicing is a recent step forward. The tool is divided into an inner and outer module, according to the topology. Anchors and/or screws are designed permitting the selection of the optimal slicing

direction, reducing final machining costs and allowing a modular extendable design for product variations (Figure 25) [43].

Figure 25. Adaptive slicing from Metal Laminated Tooling by Multiple Laser Processing – MELATO www.iws.fhg.de/~melato (Source IWS).

Layer joining is a critical step in the process; it determines the strength in the direction perpendicular to the layers and has great influence on the functionality of the final tool and the economics of the process. Layer diffusion welding is shown in Figure 26. Steel soldering with copper solder and ultrasonic consolidation of aluminium foil is shown in Figure 27 [26] [129]. Several joining options together with their respective applications are given in Figure 30 [43].

Figure 26. Layer diffusion welding: layer boundaries visible, local interlayer grain produces a solid part (Source: LFT; BLZ).

Figure 27. Soldering with copper solder (left) [Temperature: 1120°C, duration 1h, with surface pressure] (Source: LFT; BLZ) and ultrasonic consolidation (right) of Aluminium 0.1 mm layer thickness (Source Solidica).

Main applications are sheet metal forming tools. An example of a forming tool for a floor panel (Figure 28) was compared with conventionally produced Zn dies and illustrates interesting benefits (Table 7). Applications in other areas (e.g. plastic injection moulds) are known on an experimental basis only and can be found in publications. [61]

6.2 Melting LM processes

As shown in Figure 11, LM melting processes use powder stock material in two ways: layer spread on

the machining melting area or coaxial delivery with the energy source. Another implementation uses wire formed stock materials.

	Die design	Production data	Slice data	Casting	Machining (laser cutting or milling)	Assembly	Total hours	
Laminate Dies Thickness 0.5 mm	50	30	10	0	40	30	160	Laser cutting 2.7 m/min
Zn Dies	50	30	120	160	40	60	460	Die: Zn Punch: Zn + NC (Milling)

Table 7. Time comparison of LOM and Zn die for floor panel die production (Source: Sekisou Kanagata Co.).

Figure 28. Forming Tool for Floor Panel RT by Laser Cut Metal Sheet Lamination (Source: Sekisou Kanagata Co.).

Figure 29. The SLM system principle: layer thickness 0.05 – 0.1 mm ; Laser Nd:YAG wavelength 1064 nm (Source ILT, MCP).

Selective Laser Melting - SLM

The selective laser melting process is described in US Patent 6,215,093 as follows: “The method is characterised in that the metallic material in powder form is applied in the form of a metallic powder free of binders and fluxing agents, that it is heated by the laser beam to melting temperature, that the energy of the laser beam is chosen in such a way that the

layer of metallic powder is fully molten throughout at the point of impact of said laser beam” [83] [84].

Figure 30. LOM layer joining options and typical practice (Source IWS).

The equipment is similar to the SLS process (Figure 29). However, the material is completely melted by the laser beam guided by a scanner. It has similarities with welding techniques. Its most significant advantage is the independence with respect to material selection. All typical metals may be thought as candidate material and most probably perform well under optimised conditions. Most available SLM systems use a Nd:YAG laser, in total congruence with the results of SLS modelling [16] [90] [116][127].

The parts reach near full density and have mechanical properties comparable to bulk material as shown in Figures 31 and 32. Notice that a significant reduction in ductility occurs. This phenomenon is well known in welding technologies and could be corrected with thermal treatments. Other experienced material data is given in Table 8 [2] [3] [82] [98].

Other material systems including Titanium for the manufacturing of parts and medical implants were experimented under similar conditions [4]. Some application examples are shown in Figure 33.

Figure 31. Micrograph showing completely compact cross-section with X and Y tracks made in stainless steel 316L (scanning strategy: alternating 90° direction) (Source ILT, MCP).

Figure 32. Comparison of SLM strength properties to the standard bulk material for stainless steel 1.4404 (Source ILT).

Material grade		Stainless Steel 1.4404	Tool Steel 1.2343	TiAl6V4
Tensile Strength	MaP	480-520	780 - 840	1200-1400
Elongation	%	10-15	2-3	1-2
Hardness	HB	220-250 HV0.1	50-54 Rockwell	380-420 HV0.3
Surface finish	µm	Rz 30 – 60 µm	Rz 30 – 60 µm	Rz 30 – 60 µm
Accuracy	+/- mm	<0.1 mm	<0.1 mm	<0.1 mm
Maximal work-piece size	X; Y; Z mm	n.a.	n.a.	n.a.
Density of parts	%	ca. 100%	ca. 100%	ca. 100%
Production rate	mm³/hr	n.a.	n.a.	n.a.

Table 8: SLM available metal material grades mechanical properties and performance.

The accuracy was improved by almost one order of magnitude by Concept Laser GmbH to values below 0.04 mm by implementing a system with linear drives positioning the scanner. The X-Y linear motor driven axes are used in combination with a YAG laser source [91]. The new implemented ideas are well described in Herzog's Patent WO 02/36331 A2 priority 30.10.2001 (see Figure 34) [39] [40].

Figure 33. Some SLM examples: a) Injection tool $R_z = 25 \mu\text{m}$, b) Titan implant, c) Thin walled 0.5 x 40 x 40 mm stainless parts, d) Heat exchanger slots 2.5x1 mm, stainless (Source ILT, MCP, FS).

Figure 34. Herzog Patent WO 02/36331 replacing the scanner mirrors with linear X-Y drives (Source: CONCEPT Laser GmbH).

Figure 35. DMD Laser Cladding System including a Feedback controller.

The accuracy improvements were approached differently by Koch and Mazumder [54]. A closed loop feedback controller system was developed (Figure 35). An optical sensor measures the layer height and controls the laser duty cycle. The duty cycle is used to control powder flow rate. The laser cladding system DMD™ (Direct Metal Deposition) is described in US Patent 6,122,564 and US Patent 6,518,541. The systems can be used also as multi

material system for local alloying. It uses a 5KW CO₂ laser source.

A further realized option is the replacement of the laser heat source with an electron beam source operating in a vacuum chamber (Figure 36) [124] [57]. During the process, paths are traced by an electron beam gun that melts the metal powder. The advantages are the higher beam efficiency and protective working chamber [8].

Controlled Metal Build-up (CMB) and Laser Engineered Net shape (LENS®)

CMB and LENS® are similar processes derived from welding, micro welding and laser cladding technologies. The energy source is usually a laser beam with a coaxial or lateral delivery system of metal powder or metal wire. The material is deposited in a molten state, layer-by-layer on to the previous molten layer. The spot may be controlled by an appropriate sensor. The process is characterised by a wide range of applicable materials.

Figure 36. Principle of electron beam sintering from CAD to metal technology. Pat: PCT WO 01/81031 A1 (Source Arcam AB).

LENS® was developed at Sandia National Laboratories and is being commercialised by several partners (appendix 1). Process details are given in [36]. Residual stress, warping and hardening are typical issues for which attempts are being made to minimise by in-situ monitoring and modelling [125].

These processes may be classified as near net shape processes since their limited spatial resolution or accuracy calls for post-processing, either by intermediate milling after each or after a set of layers are deposited, or by final milling once the whole part is built up. The absence of a full powder bed surrounding and supporting the part yield restrictions to the shape complexity and the possibility to generate overhangs. This can be solved by applying a 5-axis LM machine or by depositing separate support material around the part and combining this with 5-axes milling [102]. The greatest advantage of laser cladding processes is their unbeaten ability to produce gradient materials by applying different powder delivery nozzles that allow to gradually switch from one material to another, which is a unique feature that is of great interest to designers.

For Aeronautical applications, the AeroMet LasformSM process is used. Commercially procured materials are used and create fully dense machining pre-forms which require only modest machining (e.g. from 0.5 mm to 1.3 mm) prior to use. Because

the precursor material is in the form of metal powders, it is also possible to produce "graded alloys" across the geometry of a component via real-time mixing of elemental constituents, which is a very unique feature that is of great interest to designers. Since the AeroMet process takes place in an inert environment, it is possible to produce laser forms in niobium, rhenium and other materials, which require protective processing atmospheres. A part in Ti-6Al-4V and a comparison of fatigue crack propagation with wrought plate is shown in Figure 37.

Figure 37. Part performed and final machined part material Ti-6Al-4V and comparison of fatigue crack propagation with wrought Ti-6Al-4V plate (Source: AeroMet LasformSM).

Figure 38. CMB wire process: a) micrograph of layers in the Z direction on substrate (steel wire 1.2343), b) mould insert and parts, c) and d) mould repair (Source: IPT).

For tooling production and tooling repair applications` two systems, a wire and a powder-based system, were investigated by the Fraunhofer IPT and A. Röders GmbH in Germany in 1995 [28], with the following specifications:

- Powder: Laser Nd:YAG, wavelength: 1064 nm, power 300 W, material: 1.2314;

- The IMTI in Canada is working on Free Form Laser Consolidation (LC), focusing on materials and thin walled parts with high integrity [131]. Materials used: IN 525, stainless steel 316 L, Stellite 6 , M4 and CPM-9V tool steel. The LC IN 625 and 316L are stronger than the respective cast materials and comparable to wrought materials. Attention was paid to internal residual stresses (Table 9).

A 3D diagram of a rectangular prism. A vertical arrow points upwards from the top-left corner, labeled "Vertical direction (direction of build)". A horizontal arrow points away from the bottom-right corner, labeled "Horizontal direction". A dashed line connects the top-left corner to the bottom-right corner, representing the diagonal.

Method	Residual Stress (MPa)	
	Horizontal Direction	Vertical Direction
X-Ray Diffraction	-65	+180
Hole-Drilling	-110	+150

The development of new materials and availability of long-term consistent polymer materials for classical RP technologies is the key to success using LM as the first choice process chain for the direct production of polymer parts. Geometrical complexity and smaller component size are main incentives. The main parameters determining the preferred process choice and possibilities are: quantity, size, complexity (Figure 41).

Figure 40. Ceramic manufacturing LM system
a) principle with chamber temperature up to 900 °C with YAG-Laser b) typical ceramic parts after post processing (Source: Phenix Systems).

Here, the state of the art is rather obvious, as some actual examples demonstrate. However, the opportunities are much wider. For instance, SLS offers unlimited geometrical possibilities, since no support is required and part orientation can be selected freely without the need for jigs or fixtures.

Figure 41. Positioning for plastic part manufacturing: LM - Layer Manufacturing; MI - Micro Injection; IM - Injection Moulding.

This process starts with a polymer powder and can create complex long-term consistent parts in an economical way. The production of undercuts is entirely feasible. New geometries, unable to be produced up to now, may be accomplished and may lead to new features such as light weight assemblies. Design for LM (DLM) possibilities might be a new challenge!

Research efforts for these applications are in developing sustainable new materials and modelling of the process behaviour [15] [19] [60] [126]. New options in material mixtures or blending [17] [22], or locally controlled component properties as for biomedical application, are being developed [31] [37].

The broad existing plastics assortment delivers many future candidates. Commonly used technical materials like HDPE, POM, ABS, EPDM or specific application dedicated materials, e.g. PEEK for medical applications, are at the laboratory research stage.

Future opportunities are the multi-material systems. Gibson [32] describes various methods for developing the SLS polymer-based Rapid Prototyping (RP) process to include multiple materials. Three specific approaches are discussed along with current findings. Two approaches discuss adaptation of the SLS process to create heterogeneous models. The third approach discusses how the selective addition of a second

material to the process can improve the overall properties of SLS components. The term “Functional Gradient Multiple-Material” (FGM) is used (Figure 42).

Figure 42. SEM photo of sintered DuraForm Polyamide sintered at LP 10% with an electrical conductive path drawn on top of it (Source: Gibson).

The broad existing polymer assortment delivers many future candidates. A system successfully applied for the development of the commercial available PA-12 (DuraForm™) and PS (CastForm™) materials is described in [72] [74]. The influencing parameters are many and the final material properties are inferior to the injected polymer grade, due to porosity and only partial melting.

Figure 43. Long term consistent polymer materials for LM manufacturing.

8.1 Long-term consistent LM polymer materials properties

The availability of long term consistent polymer materials is a key issue. Figure 43 summarises the actual available grades and major mechanical properties. Many other materials are under development as for example an Elastomer EPDM

polymer at the FHS St. Gallen Switzerland; however its lasting usability has to be proven.

The process performance like productivity, consistency, accuracy, etc., features well controllable in conventional manufacturing, have to be improved in LM simultaneously with the materials issue in order to be attractive.

8.2 Some Manufacturing examples in Polymers

Medical

Combining two important features mentioned before, i.e. geometrical complexity and individual customisation in a production line, it became economically possible to replace former semi manual processes for the production of hearing aids by LM [41] [80]. The shape of the hearing aid casing is made by SLS to fit the shape of the patients internal ear (Figure 44). Obviously, the material issue is of main concern. In this case, pigmented PA 12 (Nylon) fulfils all requirements including mechanical properties and skin compatibility. Several patents have been deposited for this application.

A second success story is in the dental medicine (Align Company). The process starts by digitising the impression of a dental teeth jaw (Figure. 45). The individual teeth correction is calculated step by step with appropriate propitiatory software. For each correction stage (about 12) the new modified impression is exported as a solid design. The intermediate impressions are produced on an SLA system serving as tooling for thermoforming a set of biocompatible transparent plastic bridges. By wearing the bridges in the mouth, teeth alignment is achieved stage by stage. It is customized tooling manufacturing and indirect bridge production. Direct manufacturing of the bridge is prevented by lack of suitable SLA resin [20].

Figure 44. Production of nylon casings for hearing aids by SLS a) digital data from a wax imprint b) SLS i60-80 per layer c) pigmented shells with hearing and vent channels before and after finishing.

(Source: Siemens/Phonak/Materialise)

Figure 45. Individual set manufacturing process chain for each patient: a) dental impression, b) digitised data elaboration, c) STL forming tool data, d) tooling sets on SLA 7000 system, e) thermoformed biocompatible transparent plastic bridge, f) bridge use in mouth (Source: Align Company).

Technical

Boeing Co. has established an entity 'Production On Demand'. Air ducting for the aerospace industry is manufactured by SLS within hours on a Vanguard SLS System (Figure 46). Complex components that are difficult to manufacture via traditional technologies are quickly manufactured on that system, at lower cost and in fewer segments. The required material characteristics were met with a PA 11 derivative with fire retardant features. A dedicated material has been developed and is used at present.

Figure 46. ADM Advanced Digital Manufacturing: direct production of air ducts (Source 3D systems).

8.3 Polymers In production tooling

An industrial tooling manufacturing and production system which amalgamates several mentioned LM advantages was invented by Gale and al. (US patent 6,287,428) [29]. A manufacturing process for pulp moulds was developed. The Integral design [**Design for LM (DLM)**] based on the UG CAD software utilizes SLS technology to incorporate the tool body, back-up, support structure and screen as one system (Figure 47). The polymer screen has no negative reactions with the acids found in paper pulp from inks, adhesives, etc. The relative low forces and temperature loads allows a long life economic tooling system. The SLS process is an excellent and unique manufacturing method for such complex perforated forms.

Figure 47. SLS made perforated mould detail for fibre forming (left) and an innovative paper pulp made package for wine bottles (right) (Source: Regale Corp.).

9 MAIN FUTURE ISSUES

This paper has tried to structure and recapitulate the main moves forwards in the field of rapid manufacturing (RM) or layered manufacturing (LM). The many manufacturing opportunities offered by LM technologies create attractive new possibilities, but are not - by any means - a substitute for established manufacturing processes. The competitive advantages of LM are: geometrical freedom and material flexibility (as far as developed).

The main issues that deserve attention in the near future are:

Materials: Even though LM can already be used to process a wide range of materials (see Figure 3), a lot remains to be done to develop better base materials (powders, liquid photopolymers, etc.) that would allow the production of parts with equal strength and other material properties (e.g. thermal, chemical) than those obtained in traditional manufacturing. One may expect cases in the future where LM parts may surpass the properties yielded by traditional manufacturing as a result of LM's unique possibilities to process composite and powder metallurgical materials. For example., powder based processes (see Figure 3) might favour an enlarged use of PM parts (compared to the shift from cast HSS to PM-HSS tools for metal cutting), while many other LM processes might lead to an increased use of metal, ceramic or fibre reinforced plastics or other composite materials (e.g. cermets, MMC). It is expected that research in the coming years will still focus mainly on metals

and plastics, but may gradually shift to ceramics and composites.

Design for LM (DLM): In order to take full advantage of LM technologies, one should reconsider the way of designing parts to profit fully from the novel additional design freedom offered by those processes. LM may offer unique possibilities to produce light weight or low inertia parts (e.g. production of porous components by SLS), functional gradient materials (e.g. with CBM or LENS), complex geometries (all LM processes), micro parts (e.g. by micro SLA or SLM), etc. This design freedom might offer unique opportunities in applications like customised production (see example of hearing aids above), medical application, aerospace parts (e.g. light weight), MEMS, etc. These issues might call for research and development in the area of dedicated CAD design software incorporating design for LM modules.

From near to net-shape: Accuracy is still a major limiting factor of present day LM processes. Existing processes and process chains have to go through extensive improvements towards a reliable and secure production technology that match the state of the art in terms of quality and accuracy. All mentioned processes have similar performances in accuracy (0.1-0.2 mm / 100 mm), surface finish (Ra 5-20 μm) and low repeatability. The efforts for improvement have to start with machine design, through technological feedback systems, over technological optimisation. The combination with traditional processes in multiprocessing equipment might be explored, in particular in combinations using HSC and PKM.

Economics: The productivity is an issue that was partially improved in 3DP for instance. However, even though the processing speed of several LM processes has already improved by more than a factor of ten [58], at lot of effort is still required to further boost production rate. Moreover, the situation in the market place, due to the great divergence of machines offered and their costs, leads to exaggerated equipment and material cost. This creates a non-realistic competitive situation and hinders a broader use of those technologies.

Consolidation: Despite a large number of patents, research results and success claims, a real break through did not happen. The opportunities are there, but one may wonder what is causing the success delay? What are the reasons for the hesitating break through? Will selective laser melting, for instance, have a quicker or immediate success? In future, application dedicated equipment will probably replace the all-round systems.

10 CONCLUSIONS

In recent years, one has observed a move from Rapid Prototyping (RP), to Rapid Tooling (RT), to an embryo of Rapid Manufacturing (RM). Layer Manufacturing (LM) definitely offers interesting future potential in this latter aspect. The authors believe that three major application areas may be recognised (Figure 48). A small number of major

industrial players will probably dominate the LM market, even though numerous additional small ventures will try to penetrate the market of LM equipment and hardware or software accessories. A possible scenario is given in Figure 48:

Figure 48: Consolidation forecast for the LM technologies 2002 – 2010.

Distinction is made between:

- Concept Modellers (CM): office equipment, close to CAD peripherals, mainly based on 3D Printing technology (e.g. Objet Quadra) for production of visual 3D models for design verification. Material: low grade, but easily processable plastics (wax, photo-curing resins). Production quantity: 1 to 20.
- Rapid Prototyping (RP) and Rapid Tooling (RT) equipment: for production of functional prototypes and null-series for tests and small lots. Parts produced directly in metal or higher grade plastics, supported by complementary secondary technologies like RTV (room temperature vulcanisation), investment casting, etc. Production quantity: 10 to 500. Technologies: SLS, SLA, FDM.
- Rapid Manufacturing (RM) equipment: for near net shape production of serial parts and full functional parts. Production quantity: over 500 to several thousands. Technologies: SLM; 3DP.

It is a fact that rapid prototyping has gained a very wide acceptance over the last decade, with an estimated production of 3.55 million models and prototypes in 2001 and a steady growth of about 20%/year, a sales of 1000-1500 machines/year over the last 5 years and about 400 RP service bureaus world wide offering RP services. The market of rapid tooling (i.e. the first application of rapid manufacturing for direct and fast production of tools)

is still much more limited, but has nevertheless found numerous real applications for the production of soft tools (for limited series) and hard tools (e.g. SLS tools for series up to 100.000 shots). As for real direct rapid manufacturing of products, its application is still in its infancy, even though very promising. The real breakthrough of RM will mainly depend on cost and productivity improvements, which have to be accompanied with further technical progress in material properties and most of all in accuracy and reliability.

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13 BIOGRAPHY

Prof. Dr. Gideon N. Levy Studied at IIT (Technion Israel Institute of Technology Haifa) **B.Sc. (1966):** Mechanical Engineering (cum lauda), **M.Sc. (1968):** Control Engineering, **D.Sc. (1972):** Manufacturing Technology

- 1973-1989 AGIE AG for Industrial Electronic, Switzerland; EDM (Electro Discharge Machining) Technologies, Product management. Head of R&D AGIE.
- 1989-1995 Soudronic AG Switzerland, CTO Vice President; Welding Technologies, Technology Management
- 1996 TTA Technology Turn Around; Industrial Consulting, Start-Up companies consulting
- 1997 Head of Mechatronic department, and Head of the Centre for Reverse Engineering and Rapid Prototyping at the University of Applied Sciences St. Gallen, Switzerland.
- 2001 Head of Institute for Rapid Product Development (RPD) University of Applied Sciences St. Gallen, Switzerland

Prof. Levy's career has been mainly in advanced R&D in Mechanical / Electronic manufacturing systems in the machinery industries. Specialising in Manufacturing technologies, Technology management, Market - Product strategies, key customers, industrial scientific and technical aspects of product design and manufacture, market launch and technology transfer. Lately focusing on freeform fabrication, reverse engineering simulations and Rapid Product development techniques. A wide range of academic activities have been kept up (MTDR, ISEM, SME, CIRP, etc.) human resource management and education are ongoing activities.

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EDUCATION

1990 **B.Sc.** in Mechanical Engineering.
1993 **MBA** Business Administration and Ecology

ACTIVITIES

1991 - 1992 Mechanical design and simulation in the aeronautics
1993 - 1994 Product management in ecological engineering recycling systems
1995 - 1996 Establishing an Educational Center for Die and Tool Making in Malaysia
1996 – University of Applied Sciences St. Gallen, Institute for Rapid Product Development , Deputy Head of the Institute,
Research and project manager in freeform fabrication, reverse engineering and medical applications.

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He obtained his Ph.D. at K.U.Leuven in 1979 and worked at the Institut Teknologi Bandung (ITB, Indonesia) from 1979 till 1982. He was research engineer at the Scientific and Technical Center of the Belgian Metalworking Industry (CRIF/WTCM) and half-time consulting engineer at the national 'Stand-by CAD/CAM' service for industry (IWONL), till being nominate full-time at K.U.Leuven in 1987.

He is Active Member of CIRP, Fellow of SME, Honorary member Romanian Society of Mech. Eng.,

Member of Belgian Royal Academy Council of Applied Sciences, Board Member BSME (Belgian Soc. Mech. & Envir. Eng.), Member IMEKO/BEMEKO (International/Belgian Measuring Confederation), member K.VIV, founding board

member of companies MATERIALISE N.V. (>1997), METRIS N.V. and MIH N.V.

Appendix 1: Commercially available Direct Metal Parts manufacturing systems

- A [1] SLS, Powder, 3D systems, <http://www.3DSystems.com/>, DTM_SLS_SLA- Ceramics
- A [2] SLS, Powder, EOS, <http://www.eos-gmbh.de/>, DMLS®
- A [3] SLS, Powder, Phenix Systems, <http://www.phenix-systems.com>, SLS_ Ceramics
- A [4] 3DP, Powder, Extrudehone, <http://www.extrudehone.com/prometal.html>
- A [5] LOM, Sheets, Sekisou Kanagata Co. Ltd., <http://www.h3.dion.ne.jp/>
- A [6] LOM, Sheets, Solidica, <http://www.solidica.com/>,
- A [7] LOM, Sheets, Zimmermann, <http://www.f-zimmermann.com/fzimmermann.html>, LOM (LMC)
- A [8] SLM, Powder, Trumpf (ILT), <http://www.ilt.fhg.de/>, <http://www.trumpf.com/>
- A [9] SLM, Powder, F&S, MCP HEK GmbH, <http://www.fockeleundschwarze.de/english/fsproductsfs-rea.html>, http://www.mcp-group.de/download/mcp_realizer_monitor.pdf
- A [10] SLM, Powder, Concept Laser GmbH, <http://www.concept-laser.de>,
- A [11] SLM, Powder, Arcam AB, <http://www.arcam.com/>, SBM Beam melting
- A [12] SLM, Powder, AeroMet, <http://www.aerometcorp.com/>, LENS®
- A [13] SLM Paste / Powder, Optomec, <http://www.optomec.com/>
- A [14] SLM, Powder, POM, <http://www.pom.net/>, DMD™ (Direct Metal Deposition)
- A [15] CMB, Powder / Wire, IPT, <http://www.ipt.fhg.de/>,
- A [16] CMB, Powder, Rhoeders, <http://www.roeders.de/>,
- A [17] FDM, Wire, H&R Technology, PDM™, <http://www.hrtechnology.com/>
- A [18] Spray, MCP HEK GmbH, http://www.mcp-group.de/download/mcp_realizer_monitor.pdf,