

DMLS – DEVELOPMENT HISTORY AND STATE OF THE ART

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Abstract

This paper summarizes the state of the art of direct metal laser-sintering (DMLS) in 2004, put into perspective by a review of its history from its roots in the 1970s, and discusses the trends going into the future. Since the 1970s, DMLS has evolved from an idea to a powerful commercial technology. The "family tree" of DMLS is explained with reference to related methods such as laser-cladding, indirect metal laser-sintering and plastic laser-sintering. Key aspects of the various machine concepts are reviewed, for example regarding laser sources (CO₂, YAG, fibre lasers etc.) and powder layer generation methods (fluidized beds, blades, brushes, milling-based systems etc.), and also materials developments and process strategies. Some examples are given of performance improvements over the years. Finally, the application trends are briefly reviewed including rapid tooling, series production tooling, rapid metal prototyping and production of end-use parts.

Keywords: laser-sintering, direct metal laser-sintering (DMLS), laser-melting, laser-cladding, metals, rapid prototyping

1 Introduction

In recent years there has been an enormous growth in the interest in technologies for additively manufacturing parts in metal. Born out of the rise of so-called rapid prototyping (RP) technologies in the 1990s and driven by the vision of a future where additive manufacturing could be as widespread and accepted as subtractive manufacturing methods are today, many people and companies around the world have developed ideas, prototype methods and commercial systems using various different ways of creating metal parts. In particular, several companies have recently started developing variations of the direct metal laser-sintering (DMLS) method, stimulated by the enormous improvements achieved in that technology over the last decade. These various technologies mostly have similar basic objectives and use the same basic method, but vary considerably in the details. The aim of this paper is to identify the main variants of DMLS and the key aspects of the technology, and to summarize the variants which have been used, including a historical perspective to aid the understanding of how this technology has developed from its roots to the state of the art in 2004.

2 Definitions

The family of technologies described in this paper is still young, and there is not yet any consistent and generally accepted nomenclature for the various process variants. On the contrary, each developer and technology supplier has tended to invent their own names for

differentiation reasons, even when referring to effectively identical processes, and the literature also uses a sometimes confusing range of names. For simplicity, the key technology referred to in this paper will be defined as follows:

- **Laser-Sintering** means methods which manufacture solid parts by solidifying powder-like materials layer-by-layer by exposing the surface of a powder bed with a laser or other energy beam
- **Direct Metal Laser-Sintering (DMLS)** means laser-sintering using a metal powder so that metal parts are produced directly in the building process

It will be seen that many currently used technologies fall under the above definition of DMLS. However this does not include methods which manufacture parts by solidifying powder-like materials by injecting such powder into a moving melt-pool created by a laser or other energy beam, which will be referred to as 3D laser cladding.

3 Historical Perspective

Figure 1 summarizes the development of DMLS and its related technologies by showing key inventions and commercial developments in chronological order (vertical axis) and technological area (horizontal axis), including the main links of how particular developments have fed into later ones. Since intellectual property is a key issue in this area, as indeed in most high technology areas, the key patent applications and licensing agreements are also indicated. This section describes the history shown in Figure 1 in more detail, including reference to the terminology which has developed over this history to help explain the many names and terms currently in use.

3.1 The early days

The idea of creating metallic parts generatively by fusing together powder material using a laser beam goes back quite a long way, to more than a decade before layerwise, additive

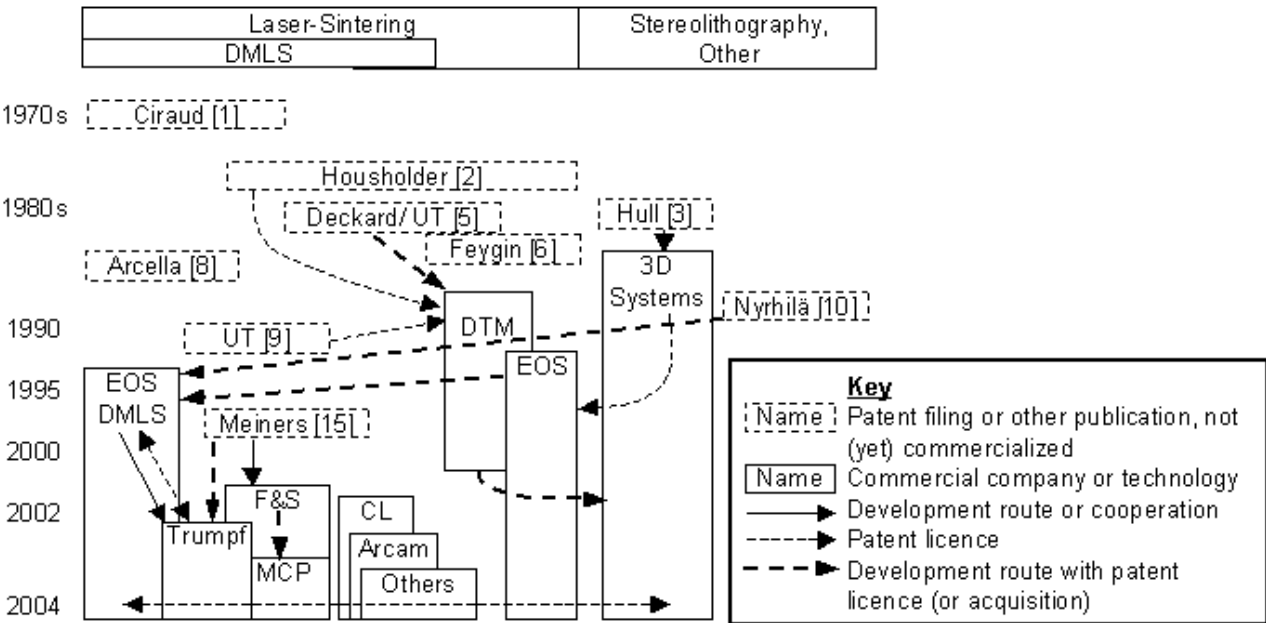


Figure 1: Summarized development and patent history of DMLS

manufacturing methods were first commercialised and the term Rapid Prototyping invented. Already in 1971 the Frenchman Pierre Ciraud filed a patent application [1] describing a method for manufacturing articles of any geometry by applying powdered material, e.g. metal powder, onto a substrate and solidifying it by means of a beam of energy, e.g. a laser beam. Ciraud's descriptions and illustrations (Fig. 2) actually bear little relation to any of today's commercial technologies, but can still be seen as a forerunner of later 3D laser cladding technologies. The basic idea and the aim of his invention relate very strongly to today's developments in additive manufacturing: "The invention makes possible the manufacture of parts which can have extremely complex shapes, without the need for casting moulds". However this idea was not yet ready for commercialisation, for example because both lasers and computers were in their infancy.

Six years later another independent, private inventor called Ross Housholder filed a patent application [2] which included a description of a system and method which bore an uncanny resemblance to future commercial laser-sintering systems (Fig. 3). The stated object of the invention was "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". In one embodiment "fusible particles are employed to form each layer which is then selectively fused by a laser beam to fuse an area in each layer which defines that portion of the article in the layers". Due to the extremely high cost of lasers at the time, Housholder was only able to fully test a variation method which did not require a laser. His invention was not commercialised at the time and remained virtually unknown until it was discovered by DTM Corporation in the course of their own patent filings (see below). DTM licensed the patent and used it for many years to protect and defend their business.

3.2 First steps to commercialisation of powder-based processes

The mid-1980s saw the first steps to commercialisation of additive manufacturing methods in general, and also of powder-based additive processes. Commercial "RP" was started by Chuck Hull, who founded the company 3D Systems to commercialise the technology described in his patent US 4,575,330, which he had filed in August 1984 [3]. Although the original patent did not explicitly mention powder, and 3D Systems did not develop any

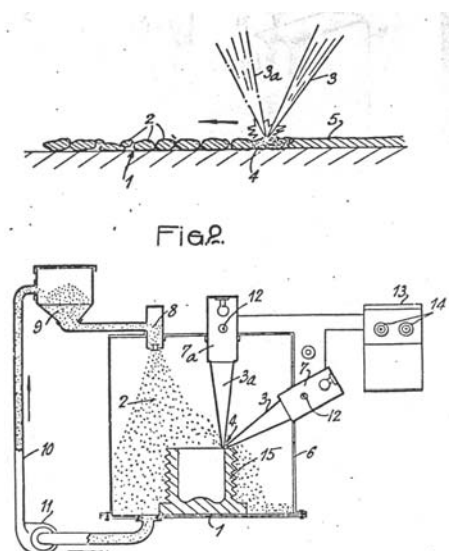


Figure 2: Ciraud's invention

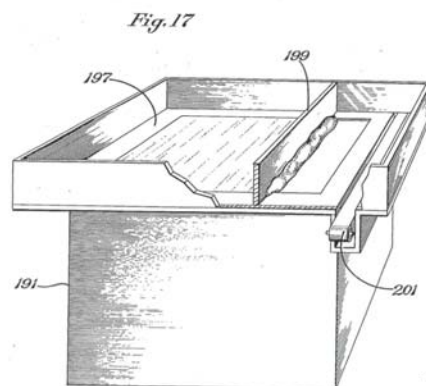
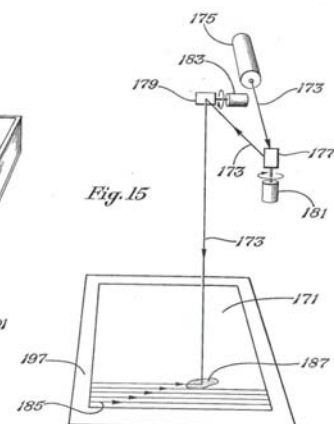


Figure 3: Housholder's invention



powder-based technology for many years, these were still very significant developments in the history of DMLS. Hull's patent was the first to describe in detail a working method and apparatus for building three-dimensional objects layer by layer, and his commercialisation aroused a lot of interest which inspired many of the subsequent developments by others. The technology which Hull described in detail and developed as a product used a vat of liquid resin, a concept which had been previously published by Hideo Kodama in Japan in 1980 and Jean-Claude André in France earlier in 1984, but not commercialised by either. However Hull realised that the concept was not limited to liquids and therefore gave it the generic name stereolithography (three-dimensional printing), and filed broad patent claims covering any "material capable of solidification" or "material capable of altering its physical state". In fact, as different processes emerged, the name stereolithography came to be associated only with the liquid resins of the first machines, but Hull and 3D Systems defined the term much more broadly. For example, in 1997 3D Systems wrote "One specific stereolithography technology is known simply as stereolithography and uses a liquid medium ... Another stereolithography technology is known as Selective Laser Sintering (SLS). SLS is based on the selective solidification of layers of a powdered medium" [4]. Hull and his colleagues built up a substantial patent portfolio covering many fundamental aspects of today's layer manufacturing technologies such as data preparation via triangulated models (STL file) and slicing, many exposure strategies such as alternating hatch directions, etc., so these "stereolithography" patents are in many cases highly relevant for DMLS and related methods. In 1997, EOS acquired the exclusive rights to the entire patent portfolio of 3D Systems for the field of laser-sintering.

Around 1986, a Masters student at the University of Texas (UT) called Carl Deckard started investigating a similar method to Hull's but using powder materials. Initially he called his method Part Generation by Layerwise Selective Sintering (PGLSS), later changing the name to Selective Laser Sintering (SLS). The resulting patent application in October 1986 described a "computer aided laser apparatus which sequentially sinters a plurality of powder layers to build the desired part in a layer-by-layer fashion" [5]. The described apparatus was essentially identical to Housholder's idea, but in this case real experimentation was done using a 100 Watt Nd:YAG laser ("chosen because of lower dollar-per-watt cost" instead of CO₂) in continuous mode with ABS polymer powder. Whilst the invention was not restricted to plastics materials, and indeed the potential for avoiding the need for casting dies or even for production facilities on-ship or in outer space were discussed, no direct processing of metal powders was reported or discussed at that stage. However the technology was licensed from UT to a company set up specifically to commercialise it, which soon became known as DTM (for "desk top manufacturing"), and the process was further developed as reported below.

Also around the same time, an independent inventor called Michael Feygin was developing similar ideas of his own, which he patented in April 1987 [6]. Feygin set up a company to commercialise his ideas which later became well known as Helisys with a machine for cutting and bonding layers of paper, but his inventions also included a powder-based process, as described in a contemporary report: "The new technique is based upon powder metallurgy and also uses a scanning laser. A layer (0.002 inch to 0.020 inch) of powdered metal is spread on a base and partially bonded by running a heated roller over the powder at a controlled pressure. The layer is then scanned by the laser in the pattern of the desired cross-sectional slice. This completes the sintering of the metal" [7]. The method was claimed to be applicable to "the manufacture of laminated molds, dies and product prototypes".

Yet another similar and parallel development was going on at Westinghouse Electric Corp., led by Frank Arcella, also resulting in a patent application in March 1988 [8]. This method could "cast shapes without using either a mold or die ... shapes are cast in a fluidized bed using a laser or electron gun ... Examples of suitable metals include stellite, stainless steel, aluminum and titanium. The preferred metal is titanium. ... If the powder is a metal, a CO2 laser is preferred". The parts were built up layer by layer in a protective gas atmosphere. To build overhangs, the fluidized bed was switched off to create a supportive powder bed, i.e. the laser-sintering method of Housholder and Deckard, but otherwise the bed remained fluidized. Arcella developed his concept further at The Johns Hopkins University and in 1997 set up the company Aeromet to commercialise his technology, specializing in the production of complex titanium structures for the aerospace industry. However he changed to a powder injection type apparatus, i.e. 3D laser cladding.

3.3 The rise of laser-sintering

The first proper commercial system for laser-sintering was the Sinterstation 2000 from DTM Corp. of Austin, Texas, the result of the research and development by Deckard, Beaman and colleagues at UT and the commercialisation efforts of DTM. First systems were shipped in December 1992. The second commercial system for laser-sintering was launched by EOS GmbH of Munich, Germany, first shipped in April 1994. Table 1 gives a comparison of some of the key features of these systems.

Both of these systems and their successor models became very successful commercial products, each having sold many hundreds until today, and led to the introduction of metal processes by the respective manufacturers, but in very different ways. DTM chose to use an indirect method by laser-sintering a polymer-coated metal powder in the Sinterstation to form a green part, followed by a furnace process to remove the polymer, bond the metal matrix and infiltrate it with a secondary metal to remove the porosity [9]. This indirect metal process called "RapidTool" was commercially released around the end of 1995. DTM was subsequently acquired by 3D Systems in 2001. The EOS developments are described below.

3.4 The emergence of Direct Metal Laser-Sintering (DMLS)

Already in 1989-1990, UT was researching the possibility of DMLS, but these "early attempts

Table 1: Key features of the Sinterstation 2000 and EOSINT (P) 350 laser-sintering systems

Feature	Sinterstation 2000	EOSINT (P) 350
Laser	CO2, 50 Watt	CO2, 50 Watt
Build volume	Ø305 mm x 410 mm = 30 litres	350 mm x 350 mm x 600 mm = 73.5 litres
Powder dispensing	From below	From above
Layer application method	Counter-rotating roller	Vibrating channel
Scanning method	Raster	Vector
Part removal	From above	From below
Early materials	Wax; polycarbonate	Polystyrene; nylon mixture

to SLS process single-phase metals such as lead, zinc or tin were unsuccessful" [10]. Various other research institutes also started similar activities in the early 1990s, and by 1994 first successes were being reported, e.g. by Fraunhofer IPT using 316L stainless steel and by the Katholieke Universiteit Leuven using Fe-Cu mixtures [11].

The first commercial system for DMLS was the result of a combination of EOS' plastic laser-sintering technology (see above) and a powder metallurgy development from Electrolux Rapid Development (ERD) of Rusko, Finland. In 1989, Nyrhilä had invented a novel powder concept for pressureless sintering with very low shrinkage [12]. He had the idea of using this concept for DMLS and discussed the idea with a number of potential partners, including providing his powder and ideas to UT, before finally a patent license and cooperation was agreed between ERD and EOS in 1994. The first test systems were developed by EOS and installed already in 1994 [13], with the first commercial EOSINT M 250 systems being installed in the summer of 1995. These used a modified version of Nyrhilä's bronze-nickel-based powder, laser-sintered in 100 μ m layers using a 100 Watt CO₂ laser. This enabled complex and massive parts to be built with a high accuracy and good surface quality, which had not been possible until then with any other direct metal process, and opened up the first real commercial use of DMLS for rapid tooling. The cooperation has continued ever since through several changes of ownership at ERD.

At the end of 1995, a German cooperative project was started with the goal of further developing the DMLS process to enable production of fully dense parts by complete melting of single component ceramic and metallic materials such as 1.4404 steel [14]. The project partners included EOS, the Fraunhofer institutes ILT and IPT, Fockele & Schwarze and some other companies. The project successfully developed parameters for building fully dense parts in certain single component ceramic and metallic materials using DMLS, which were patented exclusively by ILT [15].

3.5 The development and proliferation of DMLS

DMLS rapidly became a commercial success after the introduction of the EOSINT M 250 system, and the materials and process development proceeded quickly in the EOS-ERD cooperation. In 1997 an improved version of the powder was introduced which could be built in 50 μ m layer thickness, thereby significantly improving the surface quality (reduced stair-step effect), and in 1999 a steel powder, DirectSteel 50, was introduced based on the same low-shrinkage concept of Nyrhilä. This allowed parts with much higher strength and durability to be built. A major step in improved part quality was achieved in 2001 with the introduction of DirectSteel 20, a steel powder building with a layer thickness of just 20 μ m [16]. This was soon followed by a 20 μ m version of the bronze-based DirectMetal powder for higher productivity. Most recently, a tool steel material called DirectSteel H20 has been introduced which achieves a density of almost 100%, an ultimate tensile strength of up to 1,100 MPa and a hardness of up to 42 Rockwell C directly from the DMLS process. The EOSINT M 250 has been improved several times over the years, e.g. with increased laser power, improved atmosphere control etc., and in 2004 a completely new system generation was introduced, the EOSINT M 270, which uses a solid-state fibre laser (see details below).

Over the same period, ILT continued to develop the process with single component metals in cooperation with Trumpf AG. Trumpf decided to commercialise this version of the technology, so acquired the exclusive rights to the ILT patents and in 2002 also entered into a cooperation and patent cross-license agreement with EOS. In 2004, EOS entered into an

additional license agreement with 3D Systems whereby EOS acquired the rights to all the relevant patents of DTM and UT. In this way, EOS held rights to all the major patent portfolios relating to laser-sintering (including patents from EOS, 3D Systems, DTM, UT and ILT), and Trumpf held the same rights for the area of DMLS with complete melting of single component metals. Trumpf introduced their commercial system, the Trumaform LF 250, in 2003 and calls the process "laser forming". This system uses a disc laser and includes two separate process chambers which can each be heated up to approx. 500°C operating temperature.

In the last few years there has been a proliferation of similar technologies being developed and offered by other companies. Despite not having retain any of the patent rights from the 1995 project, Fockele & Schwarze developed a system called Realizer and named the process "selective laser melting". Concept Laser presented a machine called M3 Linear at the end of 2001 and invented the name "laser cusing" for the process. Similar machines have also been recently developed by other companies in France and Japan. Arcam has developed a similar technology using an electron beam instead of a laser beam. All of these machines use exactly the same basic principle which dates back to Housholder: a thin layer of powder is applied onto a platform, then exposed by a scanning laser or electron beam which fuses the powder together in the shape of a cross-section of the part, then another powder layer is applied and the process is repeated such that each layer is bonded to the previous layer. This proliferation shows that DMLS is maturing as an accepted manufacturing method and that there is strongly increasing belief in a high market potential. However as most of these systems are still in an early stage of technical and market development, it remains to be seen exactly how this market will develop. There are also still some unresolved legal issues, as in their normal modes of operation each of these systems uses methods covered by the EOS, 3D Systems and/or ILT patents, e.g. the parts are built onto a rigid, prefabricated platform [17] or layer thicknesses of less than 1 mm are used [18] or single component metal powder is used with full melting and protective gas atmosphere [15].

4 Machine developments

4.1 Laser sources

As already mentioned, for many years all DMLS systems used either CO₂ or Nd:YAG lasers, which were also the standard types of laser used for other laser machining processes such as laser cutting and laser welding. In recent years, with the great improvements in part accuracy and quality due to materials and process developments, the quality of the laser focus available with these laser types became a limiting factor. Parallel to this, new types of laser were being developed which offered much better beam quality, notably fibre lasers and disc lasers. Therefore the newest generation of DMLS systems generally use such lasers, for example the EOSINT M 270 uses a 200 Watt ytterbium fibre laser [19], while the Trumaform LF 250 uses a disc laser. The ytterbium fibre laser used in the EOSINT M 270 has a beam quality M² of almost 1.0, which enables it to be focussed down to around 100µm beam diameter over the entire 250 mm x 250 mm build area, which with the 200 Watt power corresponds to an average power intensity of up to 25 kW/mm². This laser also has a shorter wavelength than CO₂ lasers, which has higher absorption in metals and therefore results in higher effective power and higher possible build speeds.

4.2 Powder layer generation methods

Whilst Ciraud's "powder spraying" and Arcella's fluidized bed methods did not become popular, there are still a variety of methods used in DMLS to apply the layers of powder. EOS has so far used their patented rigid recoater blade system [20] in all their machines. Being inflexible, these can cause fairly high forces and therefore need a sturdy mechanical design, but have the advantage that they produce very precise layers. This is very important especially with very thin layers such as EOS' 20 μ m technology, where a deviation in layer thickness of even a few micrometers would cause a significant relative error. However it is also possible to use flexible systems like the brush recoater developed by Trumpf [21]. Another approach is to post-machine each laser-sintered layer prior to recoating, e.g. by grinding [22], but this has the disadvantages that it both makes the hardware more complicated and adds an additional process step to every layer.

4.4 Other aspects

Recent developments in DMLS have also introduced various other notable improvements. Originally developed and patented by EOS in 1998 for stereolithography [23], the use of a variable laser focus has now also been included in the EOSINT M 270. This enables a very fine focus for best possible detail resolution to be combined with fast, efficient exposure of large areas by using a defocussed, i.e. broader laser beam. Another approach to increasing productivity has been implemented by Trumpf: two independent process chambers so that for example one can be building while the other is heating up, cooling down or being prepared.

5 Materials and process developments

The choice of material is of course critical to the performance of DMLS for any particular intended application, as it is for most manufacturing methods (casting, forging, deep drawing, machining etc.). And as with other manufacturing methods, the process parameters must be adapted to the material in order to produce optimal or indeed any results. Understandably, the earliest investigations were performed using commercially available powder metals which had of course been developed for other manufacturing processes. However the first commercial success came with a non-standard material which had been specially tuned to perform well in the DMLS process. This is not surprising, as any manufacturing method will work best with materials which have been optimized for the specific method.

So far, the principal application of DMLS has been for rapid tooling, in particular for building tool inserts for plastic injection moulding. This application demands high accuracy and sufficient mechanical and thermal properties to withstand the moulding forces, and in some cases a highly polishable surface. However as the tool itself is not the final product, the metallurgy of the tool is otherwise unimportant so long as the main requirements are met. Blended powders which have been specially optimized for DMLS have a clear advantage here, as they provide a broader processing window and make it much easier to achieve the required accuracy. Although a toolmaker may think that a standard tool steel would be best because that is what he is familiar with, in fact he can probably get a superior combination of properties with non-standard materials. The state of the art is illustrated in Fig. 4, which shows a vertical cross-section through a part built from DirectSteel H20. This material is a specially developed powder blend containing a range of alloying elements which during the

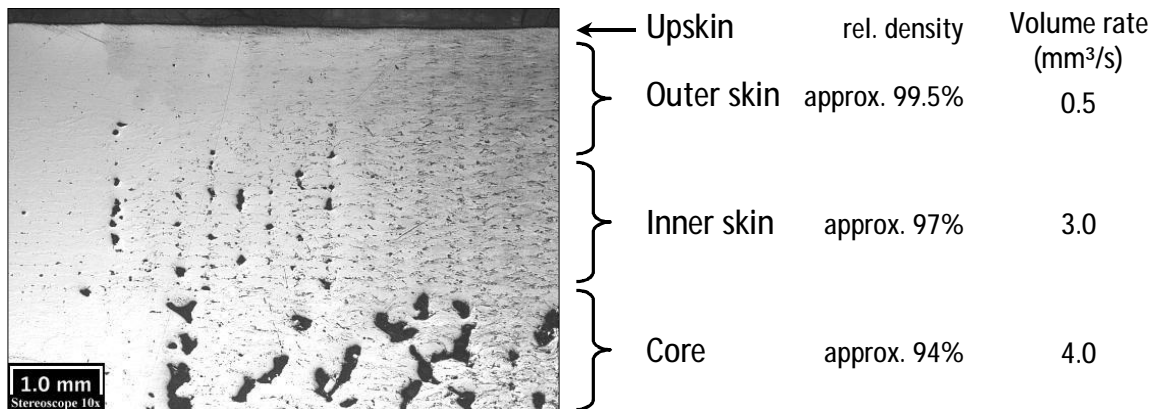


Figure 4: Vertical cross-section through DirectSteel H20 part built on EOSINT M 250 Xtended with standard parameters, shot-peened

DMLS process form a high performance tool steel. The specially tuned composition allows a very broad parameter range, offering the user a wide range of choice between for example build speed and final density, which in turn effects mechanical properties such as tensile strength. This can be used to optimize the building strategy by applying different parameters according to the requirements of different areas of the tool. The moulding surface of a tool should typically be pore-free for high polishability and have high hardness for wear resistance. This can be achieved by using a relatively slow scan speed to fully melt the metal powder and produce effectively full density, as seen in the Outer Skin region of Fig. 4. The inside of a tool typically only requires sufficient compressive strength to withstand the loading forces, so it is acceptable to build it in a porous way as shown in the Core region of Fig. 4, which can be built eight times (8x) faster than the Outer Skin region, thereby saving considerable time and cost in manufacturing the tool.

When building positive parts the requirements are typically different. For prototype parts, in many cases certain specific properties such as tensile strength or operating temperature may be sufficient, but these may need to be more uniform through the part. This can often be achieved by building the entire part with Outer Skin parameters, especially for



Figure 5: Examples of single component materials already successfully tested by EOS on EOSINT M systems. Left: impeller built in stainless steel 1.4542 (17-4 PH). Middle: impeller built in Inconel 625 (2.4856). Right: injection mould insert built in tool steel 1.2344 (H13).

thin-walled parts. For production parts typically a broader range of characteristics has to be fulfilled, and even more so than with tooling there is a strong urge at first to demand the characteristics of the conventional production materials, as this reduces the barriers to acceptability. In these cases it may be beneficial or even necessary to use a "standard" material. Some examples of parts built on EOSINT M systems using such materials are shown in Fig. 5. These have the advantage that the properties of parts manufactured by other methods in the same material can be more closely matched, but have the disadvantage that it is typically more difficult to achieve good accuracy and there is less potential for taking full advantage of the benefits of laser-sintering. In addition to the materials shown in Fig. 5, many others have been successfully tested on EOSINT M systems including other stainless steels, titanium alloy (Ti6Al4V) and pure titanium, and there is no reason why a wide range of other metals such as gold and silver alloys, aluminium alloys, other copper-based alloys, metal matrix composites etc. cannot also be processed.

6 Performance improvements

Over the years great improvements have been achieved in the performance of DMLS, through the developments of hardware, materials and process methods. The earliest commercial parts built on the EOSINT M 250 system used 100 μ m layer thickness, had a remaining bulk porosity of 20-25% and an ultimate tensile strength of around 100 MPa. Parts built today in DirectSteel H20 on an EOSINT M 250 Xtended system in 20 μ m layers can have a remaining bulk porosity of less than 0.5%, an ultimate tensile strength of more than 1,100 MPa and a hardness of up to 42 Rockwell C directly from the machine. Process innovations such as three-dimensionally variable exposure parameters, e.g. the Skin & Core method (see Fig. 4), and building the Core in thicker layers than the Skin, mean that build speed has also been optimized despite the reduced layer thickness. As mentioned above, the change to the shorter wavelength fibre laser also increases absorption and therefore enables a higher build speed, and first experience of the EOSINT M 270 machine with DirectMetal 20 powder shows that in many cases the build speed can be more than doubled compared to the EOSINT M 250 Xtended system, and further optimization is still possible.

7 Application trends

For the first years of its commercial history, DMLS was predominantly used for producing inserts for prototype injection moulds ("rapid tooling"), with a limited number of positive parts also being built as prototype products ("rapid prototyping"). Over the years, various companies and research organisations investigated other uses such as tooling for die casting, sheet metal forming, and also the limits of tool lifetime in injection moulding [24]. This was necessary because prototype tooling is rarely used to produce more than a few tens of thousands of moulded parts, then the tool is taken out of operation even if it is still perfectly operational, so the expected lifetime typically remains unknown. However in the meantime a number of projects have reported tool lifetime of up to several millions using DirectSteel 20 material, and tens of thousands of parts moulded in even highly abrasive filled plastics using DirectMetal 20 (Fig. 6). The main limitation for series production tooling was in fact not the strength or wear resistance of the metal materials, but the remaining porosity which what quality of polished surface could be achieved. The introduction of DirectSteel H20, which has been shown in independent tests to have a lower number of surface defects after polishing

than conventional tooling steel, has removed this limitation and also provided significantly higher mechanical properties, and series tooling is now a growing application area. Also gaining considerable interest is the production of positive parts, not only as prototypes but as end-use parts ("rapid manufacturing"), for example one-offs or small series of niche products. The impellers shown in Fig. 5 as well as the batch production shown in Fig. 6 give examples of this trend.

8 Summary & Conclusions

It has been shown that the roots of DMLS lie in the 1970s and 1980s, with the commercial history starting in the early 1990s and developing rapidly ever since then. In recent years numerous new variations of the same basic method have been introduced, with most of them following similar technological and application trends. It would appear that DMLS is currently on a threshold between limited application in prototyping applications and a much larger potential in the areas of series production tooling and in particular part production. The technologies required to open up this potential have already been demonstrated in principle, and the further work necessary for major success in particular application areas is ongoing or still to be done.

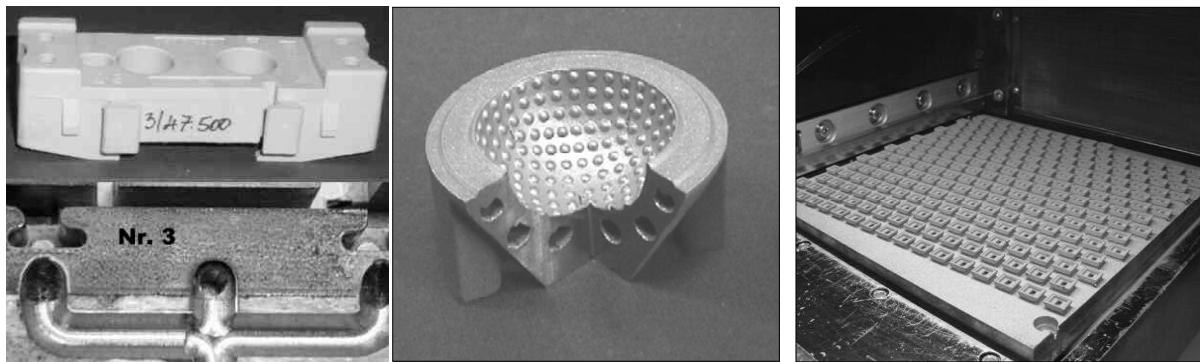


Figure 6: Application examples of DMLS using EOSINT M systems. Left: gating and moulded part after 47,500 shots of PBT+30%GF in a DirectSteel H20 insert showing virtually no wear (courtesy of RTCZ/ETI). Middle: blow mould for golfball production, sectioned to show conformal cooling channels, used to produce 4 x 5 million golballs (courtesy of Es-Tec and DemoCenter). Right: 220 positive parts produced in one build in just 7½ hours and for €4 per piece (courtesy of Alphaform RPI).

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