Whitepaper

MATERIALS FOR DIRECT METAL LASER-SINTERING

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1. e-Manufacturing and Laser-Sintering

e-Manufacturing means fast, flexible, and cost effective production directly from electronic data. Laser-sintering is a generative layer manufacturing technology and is the key technology for e-Manufacturing. Even highly complex three-dimensional geometries can be built efficiently and fully automatically, without requiring any tools or laborious milling path programming. 3D geometry data such as a CAD file or scan data are required, which are sliced into layers by the EOS software. A laser-sintering machine then builds up the required geometry by solidifying a powder material layer by layer using the energy of a focussed laser beam. The laser-sintering process allows for the simultaneous production of many different parts in one single build job. Laser-sintering can be used in every phase of the product life-cycle from rapid prototyping via series manufacturing to the production of spare parts. For further details on e-Manufacturing by laser-sintering visit www.eos.info.

2. Direct Metal Laser-Sintering (DMLS)

Direct metal laser-sintering (DMLS) creates solid metal parts by melting metal powders. The first commercial machine for DMLS, EOSINT M 250, was launched in 1995. Early materials were developed specifically for the DMLS process, i.e. with the focus on achieving a good processability and acceptable material properties for the main users' applications, as opposed to replicating a particular desired chemical composition or metallurgy. These materials can be categorized as "non-standard", because they do not correspond to any conventional metals as used in other manufacturing processes, or as "tailored", because their composition was tuned specifically for the DMLS process. The main application in the early years was (prototype) tooling (Figure 1a). In general the material of a tool is uncritical so long as it fulfils the functional requirements (e.g. strength, hardness), since the tool is not part of the final product.

Fig. 1. Application examples in DirectMetal 20: (a) injection moulding inserts, (b) functional prototypes, (c) one-off parts. Courtesy of Morris/Sentrilock, Ron Arad Associates.

Therefore big advantages can be obtained for this application by using tailored materials to optimize the speed, accuracy etc. of the build process and avoid restrictions which could be expected by using materials which have been developed for other processes having typically very different requirements. DMLS also gained increasing acceptance in this period as a method for rapidly producing functional metal prototypes (Figure 1b).
Use for end-use products was generally restricted to niche applications, and sometimes coating the DMLS material with conventional metals (Figure 1c).
In recent years both the range of commercially available materials and also the properties of the resulting parts have improved considerably.

At the same time, the focus has changed from non-standard to conventional materials. This trend has been driven by the increasing interest in rapid manufacturing, i.e. direct manufacturing of end-use parts. Since such parts are typically intended to substitute existing products or components which are produced using conventional manufacturing processes such as investment casting, die casting, forging and machining, users often demand comparable materials (as similar as possible). This is in order to achieve acceptance for the new products, and also to minimize the effort for testing, certification etc.

3. State of the art in materials for DMLS

Figure 2 summarizes the main classes of metal materials (vertical axis) and their approximate relevance, indicated by the size of the circles, for the most relevant application areas (horizontal axis). The shaded ellipses show the groups of materials developed so far by EOS for DMLS and the applications which they are suitable for. It can be seen that DMLS already covers a broad range of metal types and applications. Details of these materials are given in the following descriptions.

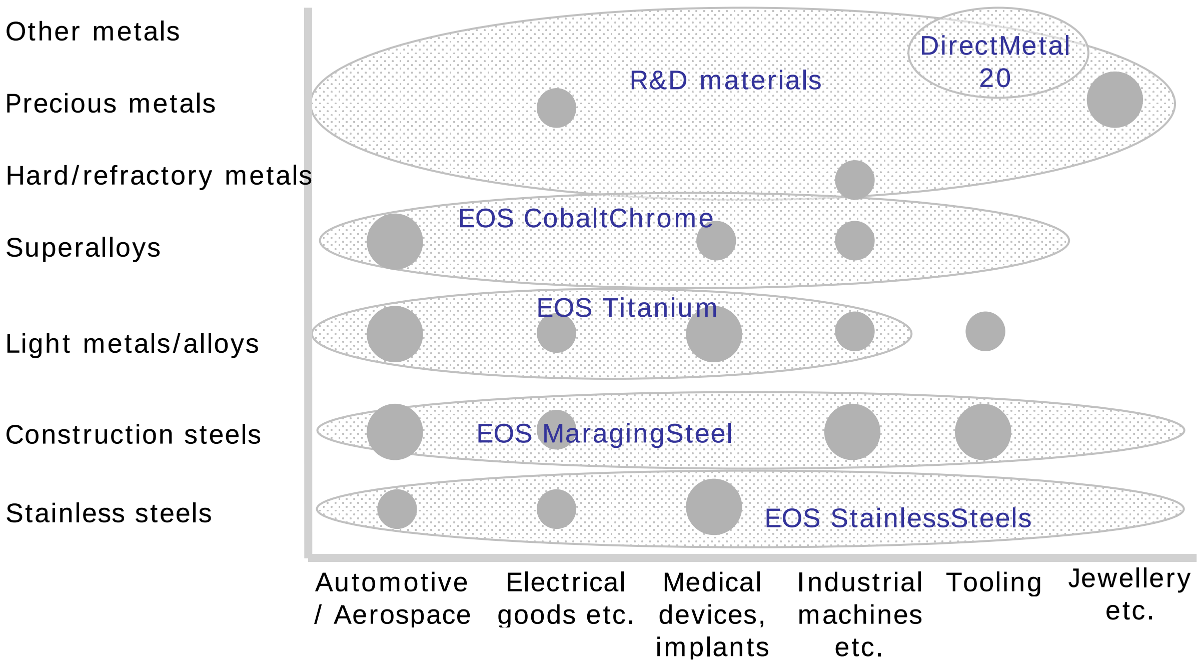

Figure 2: EOS DMLS materials covering a broad range of industrial requirements

It should be noted that, unless stated otherwise, all the named materials have been developed to commercial status, i.e. they have been extensively tested on many different machines, are produced as a series product in batches of typically hundreds of kilograms subject to defined quality assurance procedures, and are provided to users with defined process parameters which yield part properties which have been scientifically investigated.

3.1 Tailored (non-standard) materials

DirectMetal 20 is a bronze-nickel-based, multi-component metal powder, which can be processed with layer thicknesses as low as 20µm. This material was developed primarily for rapid tooling applications, and therefore optimized for high build speed (important for typically bulky tool inserts) together with excellent detail resolution and surface quality, easy polishability and adequate mechanical properties. The high build speed is achieved partly by using processing parameters which produce a porous structure in the core of the parts, as this enables very much faster building compared to full melting but still produces adequate strength. Typical applications include injection moulds and inserts for moulding up to a few tens of thousands of parts in all standard thermoplastics using standard injection parameters, and direct manufacture of functional metal prototypes, for example wind tunnel models.

3.2 Stainless steels

Stainless steels are widely used in many industrial applications and are typically characterized by good mechanical properties and corrosion resistance at relatively low cost. The first stainless steel material to be developed for EOSINT M 270 systems, EOS StainlessSteel GP1, is a pre-alloyed stainless steel with composition corresponding to US classification 17-4 and European 1.4542, which is one of the more commonly used stainless steels for engineering applications. Parts laser-sintered in this material have very acceptable ultimate tensile strength (approx. 1 000 MPa) and remarkably high elongation (around 25%), but rather low yield strength and hardenability.

Fig. 3.
Application examples.
(a) sieve in StainlessSteel GP1,
(b) tool core in MaragingSteel MS1,
(c) knee implant in CobaltChrome MP1,
(d) humeral mount in Titanium Ti64.
Courtesy of Oase, Stryker Orthopaedics, Deka/Darpa.

EOS has also developed a second stainless steel called EOS StainlessSteel PH1, with composition corresponding to US classification 15-5 and European 1.4540. This provides much higher yield strength (approx. 1025 MPa) and hardness (30 – 35 HRC) already as-built, and can be easily post-hardened using a standard H900 process to further increase both strength (yield strength approx. 1300 MPa) and hardness (40 – 45 HRC). These two materials complement each other to provide contrasting properties for different applications.
They can be used to manufacture functional prototypes, small series products, individualised products or spare parts, and are relevant for a wide range of engineering applications, for example medical instruments.

3.3 Construction and tool steels

A very wide range of conventional cast and wrought steel materials are available, and are widely used in industry for many applications. Since generative manufacturing methods such as laser-sintering tend to be most competitive in high-value applications, EOS selected a high-performance steel as the first DMLS material in this class. EOS MaragingSteel MS1 is an ultra high-strength steel with composition corresponding to US classification 18 Maraging 300, European 1.2709 and German X3NiCoMoTi 18-9-5. This kind of steel is conventionally characterized by having very high strength combined with high toughness, and the same is true of the laser-sintered parts. It is easily machinable after the building process and can be easily post-hardened to provide an ultimate tensile strength (UTS) of over 1 900 MPa and hardness of up to approx. 55 HRC by a simple thermal age-hardening process.
This kind of steel is conventionally used for complex tooling as well as for high-performance industrial parts, for example in aerospace applications. Typical applications of the laser-sintered material include (i) heavy duty injection moulds and inserts for moulding all standard thermoplastics using standard injection parameters, with achievable tool life of up to millions of parts, (ii) die casting moulds for series of up to many thousand parts in light alloys, and (iii) direct manufacture of parts for engineering applications. Real case studies reported by customers using this material include an 8-cavity series production injection mould with laser-sintered core inserts which has so far produced more than 3 million plastic parts, and a series production die casting tool with laser-sintered core which has produced 40 000 aluminium parts. In both cases conformal cooling channels were integrated into the core.

3.4 Superalloys

Superalloys are a class of metals characterized by very high strength and typically also very good performance at high temperatures. They are generally either nickel- or cobalt-based alloys. Nickel-based superalloys are mainly used in aerospace and similar applications, whereas cobalt-based superalloys are used both for aerospace and also biomedical applications such as implants. Therefore a cobalt-based superalloy was selected as the first offering for DMLS in this category, in order to address a broader range of users.
EOS CobaltChrome MP1 is a cobalt-chrome-molybdenum-based superalloy material. Parts built in this material have excellent mechanical properties (e.g. UTS greater than 1150 MPa, hardness 35 – 45 HRC), corrosion resistance and temperature resistance (maximum operating temperature of 1 150 °C). Fatigue testing has already achieved 10 million cycles without failure under a cyclic load of 0 - 440 MPa and 45 Hz frequency. Typical biomedical applications include implants, e.g. spinal, knee, hip bone and toe, while engineering applications include turbine blades and other parts for engines, cutting parts, etc. In addition, this material is suitable for any parts having very small features such as thin walls, pins, etc., which require particularly high strength and/or stiffness.
Also a special version of CoCr superalloy called EOS CobaltChrome SP1 is available which has been tuned to the specific requirements of dental restorations. This material is being used by several companies for series production of such individualised restorations.

In addition to excellent mechanical properties, corrosion resistance and temperature resistance, it has been especially developed to fulfil the requirements of dental restorations which have to be veneered with dental ceramic material. So far it is exclusively used for manufacturing dental restorations (crowns, bridges etc.).

3.5 Light alloys

Light alloys are widely used in industry. The most commonly used types are aluminium- or titanium-based. Titanium-based alloys are commonly used in applications with demanding requirements, but parts are typically expensive to manufacture conventionally, because titanium is generally difficult to cast and to machine. This makes titanium alloys an ideal target for e Manufacturing. In contrast, aluminium alloys are typically easy and cheap to cast and to machine, enabling low-cost conventional manufacture. For this reason, EOS chose to enter the light alloys area with titanium materials first.
EOS Titanium Ti64 is a pre-alloyed Ti6Al4V alloy. This well-known light alloy is characterized by having excellent mechanical properties and corrosion resistance combined with low specific weight and biocompatibility. DMLS parts in Ti6Al4V exceed the strength and hardness of forged parts, but have slightly lower elongation. Typical applications include parts requiring a combination of high mechanical properties and low specific weight, e.g. structural and engine components for aerospace and motor racing applications, etc., and biomedical implants. Also available are an ELI (extra-low interstitial) version of Ti6Al4V, and commercially pure titanium.

3.6 Other classes of metals

In addition to the materials mentioned specifically above, many other materials have also been successfully processed by DMLS. These include other stainless and tool steels, other light alloys, hard metals, refractory metals and precious metals (gold, silver etc.).

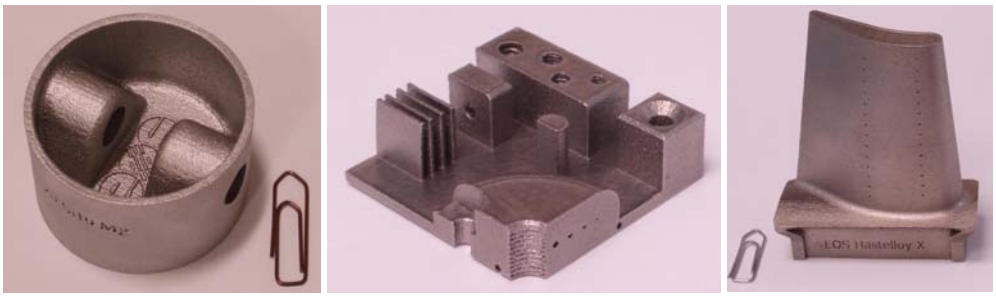

Fig. 4.
Parts built on EOSINT M 270 systems:
(a) AlSi10Mg,
(b) Inconel 718,
(c) Hastalloy X.

Figure 4 shows a selection of parts built in such materials. It is to be expected that at least some of these will be developed to commercial status in the near future. Parts have also been successfully built in non-metallic materials such as ceramics and metal-matrix composites (MMCs).

4. Differences between laser-processed and conventional materials

Since different manufacturing methods generally produce different properties if applied to the same material, for example cast Ti6Al4V has different properties to wrought Ti6Al4V, it is logical to expect that also DMLS parts will differ at least slightly from conventional parts in the corresponding material. This is indeed generally the case, as illustrated by the following examples. It is important to note that a difference in a property compared to an alternative production method can be considered an improvement or a deficit, depending on the individual application or case.

Example 1: It is known that metal parts produced by laser-based methods often have much finer grain size than cast or wrought parts in comparable material. This is generally attributed to the very rapid resolidification due to the rapid conduction of heat out of the melted zone as soon as the scanning laser spot has moved on. An example is shown in Figure 2, which shows micrographs in various magnifications of a part built in EOS CobaltChrome MP1 on an EOSINT M270 system using recommended standard parameters. At the highest magnification (5000x SEM) it can be seen that the grains have a typical size of approx. 0.3 – 0.6 µm.

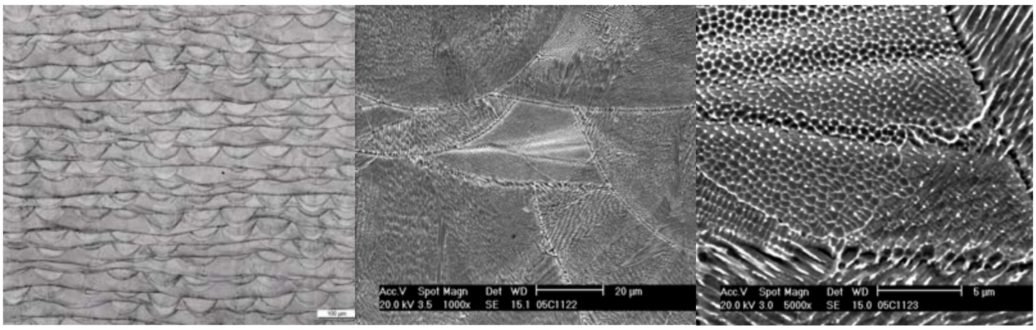

Fig 2: CobaltChrome MP1 samples, laser-sintered on EOSINT M 270 and etched.
(a) 10x optical micrograph.
(b) 1000x SEM micrograph.
(c) 5000x SEM.

Example 2: Conventionally cast or wrought components in 17-4 PH / 1.4542 steel can be post-hardened by thermal post-processing, which typically involves austenite conditioning (solution treatment) followed by transformation cooling (quenching or air cooling) and then precipitation hardening, e.g. at 482°C (900°F) for 1 to 4 hours. The result is increased strength and hardness. When such post-processing was first tested with laser-sintered parts in EOS StainlessSteel GP1, it was surprising to find that such processing (e.g. H900) actually reduced the tensile strength instead of increasing it.
Subsequent investigations indicated that this unexpected behaviour is caused by the formation of a duplex-type steel structure with interlocked phases of austenite and martensite/deltaferrite during the extremely rapid melting and re-solidification. Figures 3a and 3b illustrate this effect.
During conventional heat treatment, the duplex-type structure remains and subsequent martensite formation is hindered, which explains the different results.

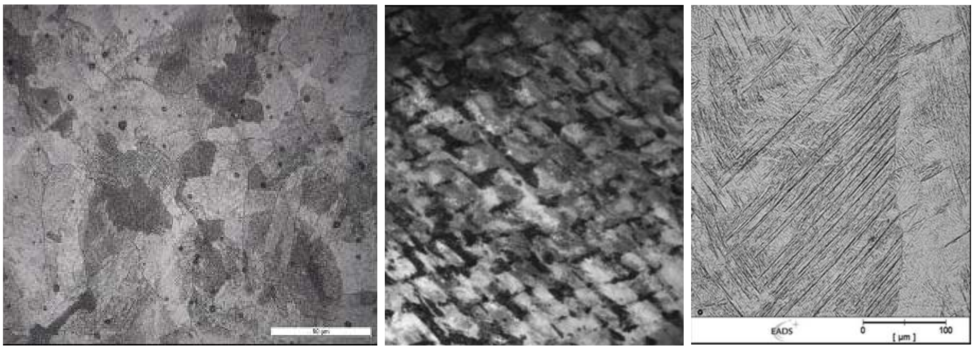

Fig. 3:
(a) StainlessSteel GP1, 50x micrograph, etched.
(b) StainlessSteel GP1, low magnification TEM bright field.
(c) Titanium Ti64 optical micrograph. Courtesy of EADS.

Example 3: When building parts up layer-by-layer by sequentially melting and re-solidifying individual lines of material, one intuitively expects to see a resulting structure such as that of cobalt-chrome in Figure 2 with "weld lines" and fine grain structure. However laser-sintered parts in Ti6Al4V show no such layered structure. Instead a dendritic structure is observed with crystals oriented perpendicular to the applied layer, and having a height much greater than the layer thickness (Figure 3c).

This phenomenon can be explained by the laser energy of each vector remelting part of the previously solidified layer below and thereby removing the existing boundary, and the subsequent recrystallization causing the crystal to grow through the layers.
It should be noted that the material structure and properties depend on the build strategies (e.g. laser exposure patterns) and parameters used. The examples quoted above all refer to specific build situations and the results may vary when different parameters are used.

5. Perspectives for future materials developments

The introduction of conventional materials for DMLS has been successful in increasing acceptance, and has already led to many requests for additional materials. Since a very broad range of metal materials can be processed by DMLS, it is to be expected that the number and range of commercially available materials will continue to grow. This trend is likely to include:

- (a) additional material types within an existing class, e.g. nickel-based superalloys, different stainless steels, etc.
- (b) new classes of materials, e.g. precious metals, hard metals, ceramics, completely new alloys or composites (tailored materials), etc.
- (c) variations on existing materials, e.g. versions having different grain size distributions (for example coarser grains for thicker layers and higher build speed, or finer grains for higher detail resolution) or different levels of purity / quality control / documentation.
- (d) customer-specific materials.

In some cases it is already occurring that a different base material is intentionally chosen for DMLS compared to the conventional method which it is substituting; for example, in many cases the DMLS material of choice for products which are conventionally produced in 17-4 PH steel (1.4542) will be EOS StainlessSteel PH1. It is therefore to be expected that as DMLS and e-Manufacturing become more established and accepted, the trend will revert somewhat to tailored materials, either based on different conventional materials or completely new, previously unknown formulations. In the end, for most applications the chemical composition is not as important as the part properties.

6. Summary and conclusions

It has been shown that many different materials can be processed by DMLS to produce high quality parts for a wide range of applications, and already a variety of materials covering the most important classes of metals for manufacturing (steels, superalloys, light alloys etc.) have been brought to commercial status, i.e. are suitable for series production of end-use parts. The range of available materials has been growing rapidly and can be expected to keep doing so.

Both tailored (non-standard) and conventional metals have been developed for DMLS. In recent times the trend has been towards conventional materials, in order to improve the acceptance of this new manufacturing method in established applications. In many cases this has already enabled a partial substitution of conventionally manufactured products by e-Manufacturing, with the associated benefits of short lead-time, high freedom of design, minimized fixed costs for tooling etc., flexible manufacturing etc. This is possible where the key material properties are fulfilled by the DMLS parts.

However it is important to remember that, as with every other manufacturing method, DMLS produces unique material and part properties.

New users of DMLS parts are often surprised to find that the material properties and part behaviour differ somewhat from their expectations. The reactions vary from disappointment that the user has to consider some changes compared to what he is used to, to great excitement at new possibilities which are opened up. The surprise is typically just because DMLS is still relatively unknown and little understood in industry. At the moment this is often a hindrance to the introduction and acceptance of the new method, but as the awareness of the technology and its benefits increases, this limitation can be expected to increasingly be replaced by new opportunities.

DMLS offers an ideal platform for developing completely new products and applications. For one thing, the difficulties of substituting existing production methods and procedures do not exist in such cases, at least not to the same degree, but also because DMLS creates the material (i.e. the metallurgy) locally in the laser focus during the production of the part. This gives unprecedented possibilities to create new, tailored materials and/or material gradients, including materials which cannot be manufactured by other means (e.g. non-castable alloys). Due to the additive build-up of the parts, it is also possible to vary the geometry and the internal structure of the material in a huge variety of ways, which offers fascinating possibilities for designing and optimizing part properties and behaviour by geometrical means, in addition to chemical means. Examples are bionic design, stress-optimized fill structures, etc.

About the authors

Dr. Mike Shellabear graduated in mechanical engineering at Loughborough University of Technology, England, where he also gained his Ph.D in vibration analysis using laser interferometry. In 1991 he joined EOS, Germany, as Engineering Manager for 3D Optical Metrology, later taking over responsibility as Market Development Manager and then Assistant to the Management Board. Following that, he was appointed Product Manager for the Direct Metal Laser Sintering (DMLS) technology and became its Vice President in 2006. He has more than 15 years of experience in the Rapid Prototyping & Manufacturing industry.

Olli Nyrhilä holds a master's degree in Physics with the main interest in materials science. He started developing metal powders and related manufacturing methods in 1987 with Electrolux Rapid Development, and in the early 1990's developed the first materials for DMLS as a cooperation partner of EOS. The cooperation continued for several years and resulted in the foundation of EOS' Finnish subsidiary in 2000. He now heads the material and process development team at EOS Finland and is responsible for coordinating new materials development strategy.