PRODUCTION OF METALLIC PARTS BY ADDITIVE MANUFACTURING

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ABSTRACT
The additive manufacturing technology has been introduced early in 1980s, since then it became one of the key technologies to manufacture everything from prosthetic limbs to aircraft parts in many industries.

In this paper, the advantages of forming of metal-based materials by additive manufacturing technologies are investigated. Several different metal powders for additive manufacturing and their properties and applications for biomedical field are introduced. Additive manufacturing is compared with standard manufacturing technologies and their mechanical and physical properties of manufactured products are also described.

Keywords: Additive Manufacturing, Direct Metal Laser Sintering, DMLS, 3D printing, Biomedical

METALİK PARÇALARIN EKLEMELİ İMALATLA ÜRETİMİ

ÖZET

Eklemeli üretim teknolojisi 1980'lerin başlarından itibaren gelişmeye başladı, bugün takma bacaktan uçak parçalarına kadar her şeyin üretmesini olanaklı kılan bir teknoloji halini almıştır.

Bu çalışmada, metal esaslı malzemelerin eklemeli-kat kat üretim yöntemiyle şekillendirilmesinin avantajlarına değinilmiştir. Eklemeli üretimde kullanılan metal tozlar, özellikleri ve kullanım alanları biyomedikal alan ekseninde tanıtılmıştır. 3D Baskı ürünler, standart üretim metotlarıyla şekillendirilmiş ürünlerle karşılaştırılmış, mekanik ve fiziksel özellikleri de açıklanmıştır.

***Anahtar kelimeler*:** Eklemeli Üretim, Direkt Metal Lazer Sinterleme, DMLS, 3D Baskı, Biyomedikal

1. ADDITIVE MANUFACTURING

Fine metal powders are used to produce metal parts in additive manufacturing. Roughly to explain, layer by layer melting and solidification processes turns this fine metal powder into a

3D geometrical parts which can be deployed in many different industries. The structure and properties of engineering parts produced by this method is different compare to conventional production methods such as casting, plastic deformation, machining, welding etc. As experienced in all production methods, the properties of product depends on charge material (powder), production technology and process parameters. Laser sintering or electron beam sintering in additive manufacturing results in satisfactory and reliable material property. The aim of this study is to establish a relationship between material, process and metallurgical property for laser based additive manufacturing of metallic components.

Additive manufacturing of metal-based materials deploys very fine metal powders. These powders passing solidification process in layers are produced gradually to a desired (predesigned) geometry. Additive manufacturing is completed within a few hours by turning three-dimensional CAD data into real parts. Manufactured parts are either prototypes (models) or final products. 3D Printing is also referred as e-manufacturing in general and direct metal laser sintering (DMLS) for metals only manufacturing. With this process a thin layer of metal powder is melted and rapidly solidified layer by layer using laser beam. Electron beam sintering (EBS) is another technological achievement in additive metal manufacturing.

In Figure 1, additive manufacturing process is explained briefly in three steps. Many consumer goods, machinery parts, shoes - architectural models, body parts and complicated shapes can be produced by 3D printing as a first step. Any changes on products can be corrected in considerable shorter times. Today, many personalized goods, millions of dentures and teeth are manufactured using 3D printing technologies. In near future, 3D printers will make not only prototypes but many finished goods too, from aircraft parts to customized kitchen gadgets, medical implants and personalized jewelry. In this way, very complex three-dimensional geometries, and deep holes with details such as cooling channels, in general and personalized medical applications (in the form of implants) is produced [1-7].

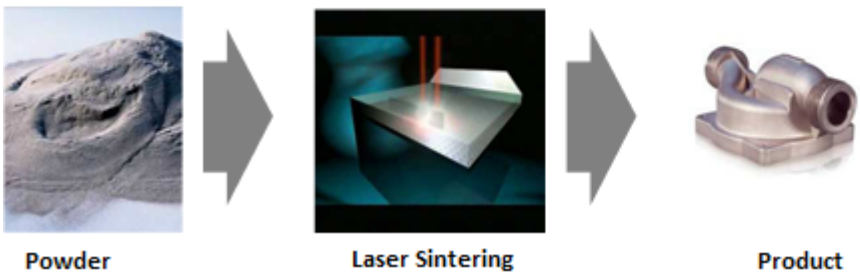


Figure 1 Direct metal laser sintering (DMLS) production method from powder to product [1].

Additive manufacturing creates layered structure with anisotropic properties. Anisotropic structure cannot be completely homogenized by heat treatment. This fact gives importance in terms of design and makes it necessary to take the worst state. Parts produced by additive manufacturing carry the risk of cracks and the risk is reduced by heat treatment. Surface roughness is a function of geometry. Stress points and crack propagation can generally occur in inland areas. This situation makes specifications complex, requires a good surface polishing. The risk of deformation, especially in the lower plate can be seen and additive support is used at the point of production. Obviously, stress–relieving heat treatment solutions and other precautions naturally increases the cost and production time will be longer. When the surface area of powder increases, the oxygen content is raised and negative structural effects are expected. Lower than 10 ppm oxygen induced powder is preferred and control oxygen atmosphere must be provided during production. Flat – plate structured porosity (5-50 micro meters) can be seen in final product.

Additive manufacturing is very suitable for medical applications since fields' need on personalized parts opens many new horizons for this ever-rising technology. Especially, Cobalt-Chromium alloys and titanium alloys are increasing their market share and they are exploited in many more promising applications. In this study, the medical applications of additive manufacturing, shortly DMLS of indicated alloys are explained in details.

2. COBALT – CHROMIUM (CoCrMo) ALLOYS

Cobalt–Chromium (CoCrMo) alloys are in use as prototypes and series of final product. Key characteristics of Cobalt-Chromium alloys are high strength, high temperature and corrosion resistance and biocompatibility. 3D Printing of this alloy fits in to chemical and mechanical specifications of ISO 5832-4 and ASTM F75 (cast CoCrMo implant alloys), and most of ISO 5832-12, ASTM F1537 (wrought CoCrMo implants) and medical device directive 93/42/EEC (for dentistry).

CoCrMo alloys have typical applications as medical implants. This alloy, by satisfying high–temperature engineering applications (turbine blades) has an important share. Alloys include high cobalt (62%), chromium (28%) and molybdenum (16%). Nickel in the alloy is not desirable and should be very low (<0,10%) (Table 1).

Table 1 Cobalt – chromium alloys [1].

Element	Content (by weight)
Cobalt	60 – 65 %
Chromium	26 - 30 %
Molybdenum	5 - 7 %
Silicon	$\leq$ 1.0 %
Manganese	$\leq$ 1.0 %
Iron	$\leq$ 0.75 %
Carbon	$\leq$ 0.16 %
Nickel	$\leq$ 0.10 %

CoCrMo alloy has advanced mechanical and physical properties as shown in Tables 2-4.

Table 2 The mechanical properties of Cobalt – Chromium alloy 20°C [1].

Property	As built	Heat treated (1)
Tensile strength		
- horizontal (XY)	1350 ± 100 MPa	1100 ± 100 MPa
- vertical (Z)	1200 ± 150 MPa	1100 ± 100 MPa
Yield strength (Rp 0.2 %)		
- horizontal (XY)	1060 ± 100 MPa	600 ± 50 MPa
- vertical (Z)	800 ± 100 MPa	600 ± 50 MPa
Elongation at break		
- horizontal (XY)	(11 ± 3) %	min. 20 %
- vertical (Z)	(24 ± 4) %	min. 20 %

(1) 6 hours at 1150°C

Table 3 CoCrMo alloys physical and thermal properties [1].

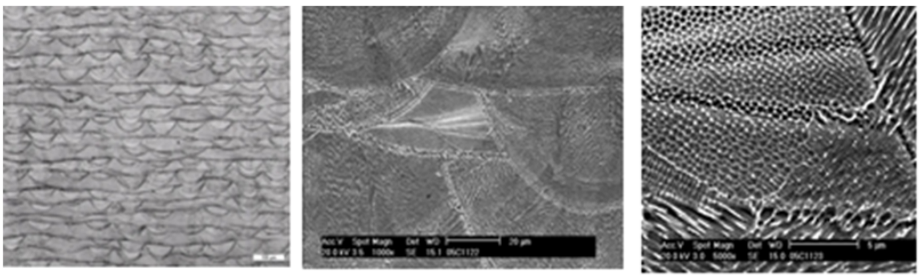
Property	Value
Relative density	approx. 100 %
Density	8.29 g/cm³
Thermal conductivity	
- at 20 °C:	13 W/m°C
- at 300 °C:	18 W/m°C
- at 500 °C:	22 W/m°C
- at 1000 °C:	33 W/m°C
Coefficient of thermal expansion	
- 20 – 500 °C	13.6 x10^{-6} m/m°C
- 500 – 1000 °C	15.1 x10^{-6} m/m°C

Table 4 CoCrMo alloys used in dentistry for a sample of certified (Commercial name: EOS Cobalt–Chromium SP2: EOS system, the EOS M 270 INT certified material for crowns and bridges for) [2].

Element Content (wt %)	Features	
Co:63,8	The relative density	Approx. 100%
Cr:24,7	Density	8,5 g/cm³
Mo:5,1	Yield (Rp0,2%)	850MPa
W:5,4	Ultimate tensile strength	1350MPa
Si:1,0	% Elongation	3%
Fe: max. 0,50	Young module	Approx. 200 GPa
Mn: max. 0,10	HV10	420HV
Prohibited elements. Ni, Be, and Cd acc. to EN ISO 22674	Thermal expansion coefficient (25-500°C)	14,3x10E-6m/m°C
	Thermal expansion coefficient (20-600°C)	14,5x10E-6m/m°C
	Melting range	1410-1450°C

CoCrMo based super alloys used for the production of crowns and bridges are given in Table 4. This, in comparison with other metal alloys, suitable for dental sector, biocompatible (CE 0537), certified and is very inexpensive.

The microstructural characteristics of CoCrMo alloys are given in Figure 2. Layered structures, micro and macro features are remarkable and facinating.



a) 10X OPTIC b) 1000X SEM c) 5000X SEM

Figure 2 CoCrMo alloy microstructure a) obtained by completely melting appears dense layered structure, b) Grain shape, c) Details (very fine 0,3 to 0,6 micrometer size beads) [1,2].

3. TITANIUM ALLOYS

Standard titanium alloys are used in implants and various industrial applications. Table 5 gives the important properties of titanium alloys.

Table 5 Summary of the most important Ti alloys [1, 2].

Material name	Composition	Typical applications	Tensile strength (*) [MPa]	Elongation at break (*) [%]
Ti CP grade 1	Ti; O <0.18%; N <0.03%	Medical and dental	240	24
Ti CP grade 2	Ti; O <0.25%, N <0.03%	Medical and dental, chemical industry	345	20
Ti CP grade 3	Ti; O <0.35%, N < 0.05%	Medical and dental	450	18
Ti CP grade 4	Ti; O < 0.40%, N < 0.05%	Medical and dental	550	15
Ti6Al4V (grade 5)	Ti; Al 6%; V 4%; O <0.20%, N < 0.05%	Aerospace, medical, dental etc.	895	10
Ti6Al4V ELI	Ti; Al 6%; V 4%; O <0.15%, N < 0.05%	Medical and dental		

CP = commercially pure, ELI = extra-low interstitials
(*) Source: Euro-Titan Handels AG, Solingen, Germany

Key characteristics: Light weight with high specific strength (strength per weight), corrosion resistance and biocompatibility. Typical applications are aerospace, engineering applications and biomedical implants.

3D Printing product carries superior properties and production standards are better than conventional types. Table 6 gives mechanical properties of the alloy of Ti 64 and Table 7 gives the compositions.

Table 6 Ti64 mechanical properties [1, 2].

Property	As built	Heat treated [1]
Tensile strength		min. 930 MPa
- horizontal (XY)	1230 ± 40 MPa	typ. 1050 ± 20 MPa
- vertical (Z)	1200 ± 40 MPa	typ. 1060 ± 20 MPa
Yield strength (Rp 0.2 %)		min. 860 MPa
- horizontal (XY)	1060 ± 40 MPa	typ. 1000 ± 20 MPa
- vertical (Z)	1070 ± 40 MPa	typ. 1000 ± 20 MPa
Elongation at break		min. 10 %
- horizontal (XY)	(10 ± 2) %	typ. (14 ± 1) %
- vertical (Z)	(11 ± 3) %	typ. (15 ± 1) %
Hardness	320 ± 12 HV5	

Chemical composition corresponds to ISO 5832-3, ASTM F1472 and ASTM B348. Chemical properties parts fulfil requirements of ASTM F1472 (for Ti6Al4V) and ASTM F136 (for Ti6Al4V ELI) regarding maximum concentration of impurities.

Table 7 Ti64 alloy chemical composition [1, 2].

Element	Content (by weight)
Titanium	balance
Aluminium	5.5 – 6.75 %
Vanadium	3.5 – 4.5 %
Oxygen	< 2000 ppm
Nitrogen	< 500 ppm
Carbon	< 800 ppm
Hydrogen	< 150 ppm
Iron	< 3000 ppm

Ti64 alloy with superior physical and metallographic properties are presented in Table 8 and Figure 3.

Table 8 Ti64 alloys physical and thermal properties [1, 2].

Property	
Relative density	approx. 100 %
Density	4.41 g/cm³
Maximum long-term operating temperature	approx. 350 °C

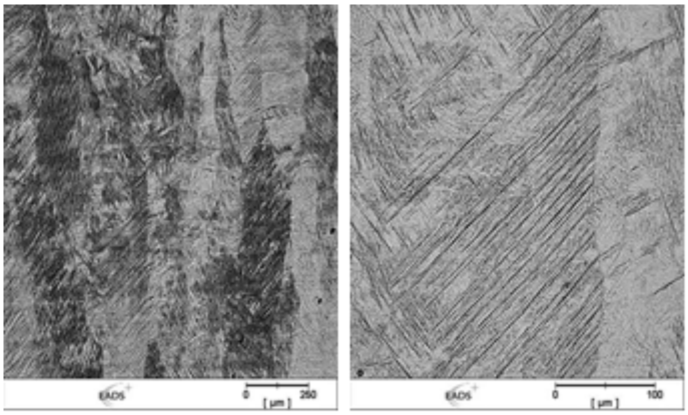


Figure 3 Ti64 alloy Widmanstatten martensitic structure [1, 2].

4. APPLICATION EXAMPLES

Biomedical applications of 3D print CoCrMo and titanium alloys are given in Figure 4-11.

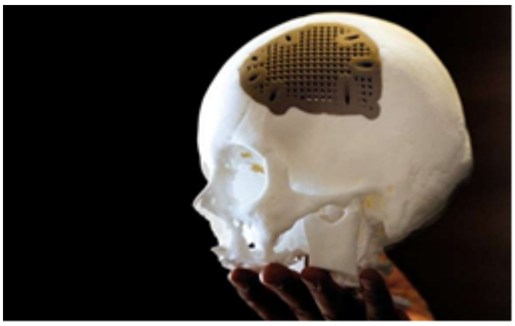


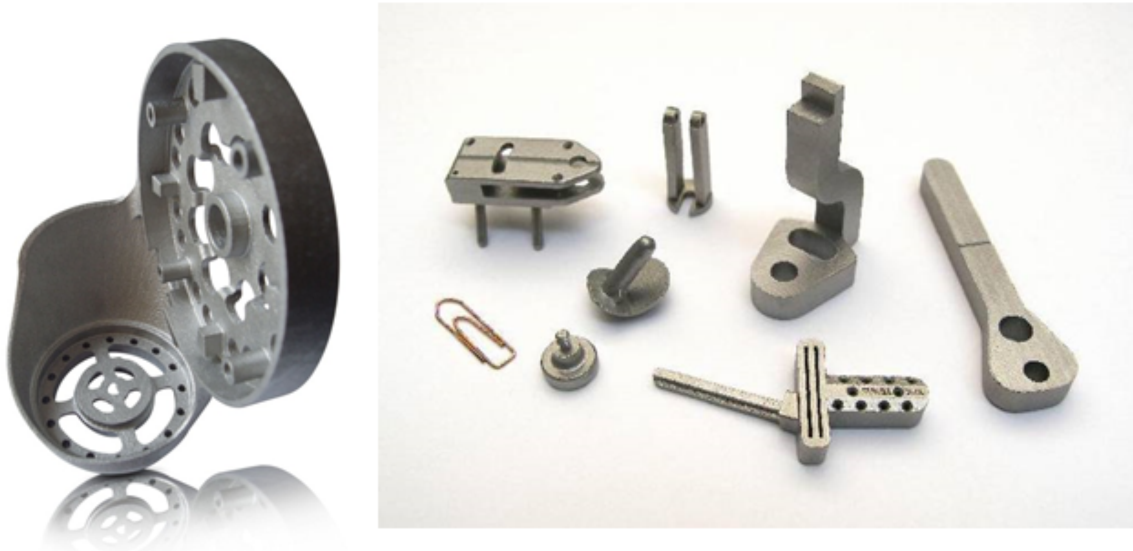
Figure 4 Head injury and solution by 3D print PEEK material or titanium plate (general usage). PEEK enabling bone in growth [2].

(a) (b)

Figure 5 Medical applications. (a) Spinal (waist) implants, (b) Finger implants Ti64 [2].

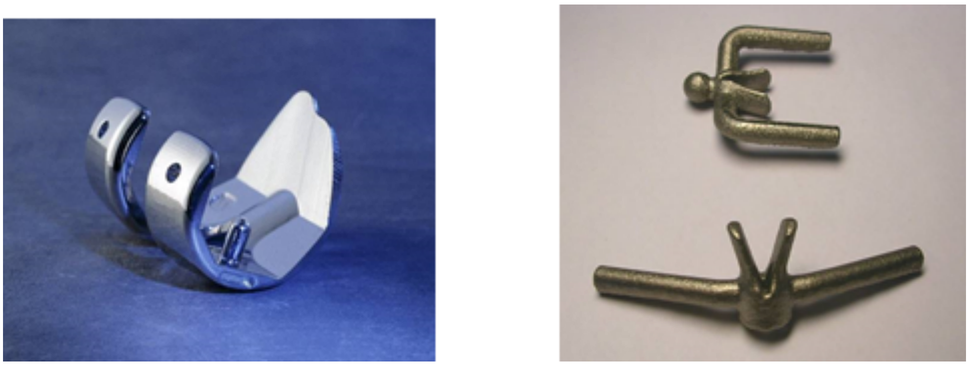
Figure 6 Direct Metal Laser Sintering (DMLS) CoCrMo alloy for dental applications [2].

Figure 7 Batch of finger implants in EOS CobaltChrome MP1[2].



(a) (b)

Figure 8 Medical applications. (a) Humeral mount EOS Titanium Tİ64 for a fully integrated arm, (b) Medical parts in EOS Stainless Steel GP1 [2].



(a) (b)

Figure 9 Medical applications. (a) Replacement knee joint in EOS CoCr MP1, (b) Spinal implants in EOS Titanium Ti64 [2].

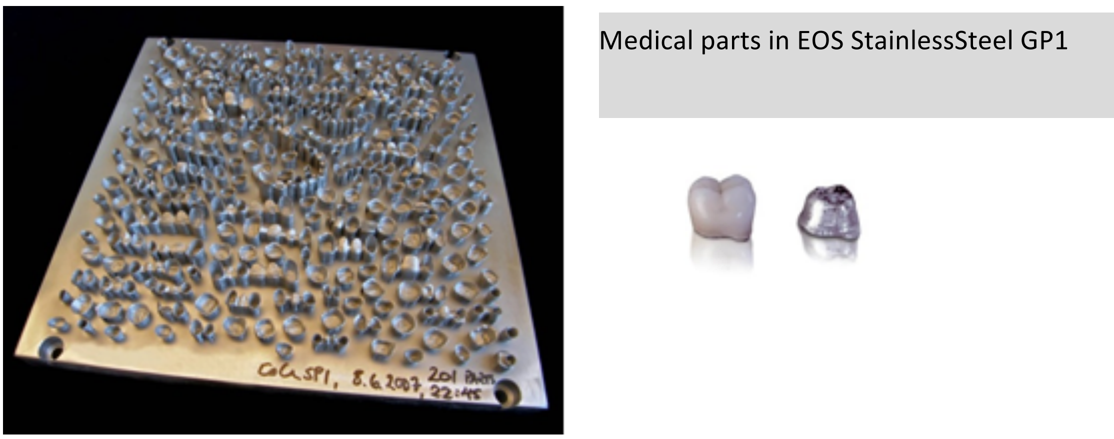


Figure 10 Dental applications [2].

(a) (b)

Figure 11 Dental applications. (a) Aligner in EOS CoCr MP1, (b) Dental device in EOS Titanium Ti64 [2].

5. RESULTS

The additive manufacturing or 3D printers, now used to manufacture everything from architectural prototyping to aircraft turbocharge turbines. Many researchers prefer the term "additive manufacturing" rather than "3D printing" to stress out the "manufacturing" aspect of the technology. One reason is that printing is not quite the right term for some of the technologies given under this subject. Whereas hobbyist-scale 3D printers typically build a product from filaments of plastic, selective laser melting zaps successive layers of powders with a laser or ion beam hardening only certain bits. The term, 3D printing gives a sense of small scale office work.

3D printers are in use for either prototyping or final product. Today, 28% of 3D printing outcomes are focusing on the final production. In 2016, it is reckoned that this ratio will exceed 50% and will go up to 80% by 2020. It will never expand to 100% since other technologies will always be still in use.3D printing presenting an ever-growing trend on medical field.

Building body parts and living tissue with a 3D printing or additive manufacturing is a novel area of research and becoming a growing business. This technology has two promising material centred in medical field, namely; cobalt – chromium alloys and titanium alloys.

The field of 3D bio-printing is promising even bigger: to create human tissues-layer by layer- for research, drug development and testing, and ultimately as replacement organs, such as a kidney or pancreas for patients desperately in need of a transplant. Various bioprinted organs and miniature body parts like kidney could also be manufactured on demand.

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