Comparative Analysis of the Components Obtained by Additive Manufacturing Used for Prosthetics and Medical Instruments

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This paper presents a comparative study on the microstructural and mechanical characteristics of a biocompatible titanium and Co-Cr alloys used in prosthetics implants and medical instruments fabrications. The samples used for the analysis were obtained by applying the additive manufacturing process called Direct Melting Laser Sintering. Following the analysis of the results obtained for the two sets of samples it was observed that the thermophysical properties of the materials influence the quality of the obtained surfaces.

Keywords: prostheses, medical instruments, titanium alloys, Co-Cr alloys, DMLS

Metallic materials are often used for different types of prosthetics or medical instruments. Taking into account the excellent mechanical properties and their biocompatibility, titan and Co-Cr alloys are best used in medical field. Lately, it is desired to improve the properties of the used materials, but also the development of new manufacturing technologies.

By the laser rapid prototyping Direct Melting Laser Sintering (DMLS) version, the orthopaedic implants or medical instruments are built by layer-by-layer melting in three-dimensional shape, with high precision, based on 3D CAD model. The rapid prototyping process requires that the fine metal powder (ex. EOS Ti64, EOS CobaltChrome MP1, EOS CobaltChrome SP2 etc.) be applied in thin layers and completely molten with the help of a laser fascicle in the areas required by the 3D model [1-3].

The additive manufacturing (AM) processes are used for their design benefits and for personalized medical instruments and prosthetics in optimal time and quality conditions. Various medical fields have implemented AM technologies in their product development processes, mainly due to the unique characteristic, that design complexity is free of constraints. AM uses a number of materials and technologies, each with specific advantages to enable the development of improved end-use medical devices and prototypes for a wide variety of applications [4-8].

The Co-Cr and Ti6Al4V alloy are considered bio-compatible materials in medicine and presents a good balance among different properties as strength, toughness and corrosion resistance in different environments. DMLS is a rapid prototyping and is ideal for smaller prototypes, custom prostheses parts and medical instruments. All materials sintered by DMLS present a porous structure that influences the mechanical and corrosion behaviour [9-12].

Experimental parts

The main objective of the experimental part was to realize a comparative analysis of the components obtained by sintering two different metallic powders with the help of DMLS additive manufacturing. The equipment used for the analysis was EOSINT M270, and the values of the working parameters were those of specific basic settings (laser power, scan speed etc.) [1].

The EOS CobaltChrome MP1 and EOS Titanium Ti64 metallic powders, used for the components undergone the metallographic examination have been optimized especially for processing on EOSINT M systems (EOSINT M270). The chemical composition and physical properties of the used powders are presented in tables 1 and 2 [13,14].

The EOS Titanium Ti64 powder was used - it is a titanium alloy powder which has been optimized especially for processing on EOSINT M systems (EOSINT M270). Parts

Table 1
PHYSICAL AND CHEMICAL PROPERTIES OF EOS CoCr MP1 PARTS

Material	Co [%]	Cr [%]	Mo [%]	Si [%]	Mn [%]	Fe [%]	C [%]	Ni [%]	Density [g/cm³]
EOS CobaltChrome MP1	60…65	26…30	5…7	≤ 1.0	≤ 1.0	≤ 0.75	≤ 0.16	≤ 0.10	8.3

Table 2
PHYSICAL AND CHEMICAL PROPERTIES OF EOS TITANIUM Ti64 PARTS

Material	Al [%]	V [%]	O ppm	N ppm	C ppm	H ppm	Fe ppm	Density [g/cm³]
EOS Titanium Ti64	5.5… 6.75	3.5… 4.5	< 2000	< 500	< 800	< 150	< 3000	4.41

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Table 3
TECHNICAL DATA AND MECHANICAL PROPERTIES OF PARTS AT 20 °C

No.	Properties	EOS CobaltChrome MP1		EOS Ti64	
		As built	Stress relieved	As built	Stress relieved
1.	Tensile strength according to [25] - in horizontal direction (XY) - in vertical direction (Z)	 1350 ± 100 MPa 1200 ± 150 MPa	 1100 ± 100 MPa 1100 ± 100 MPa	 1290 ± 50 MPa 1240 ± 50 MPa	 1100 ± 40 MPa 1100 ± 40 MPa
2.	Yield strength (Rp 0.2 %) according to [25] - in horizontal direction (XY) - in vertical direction (Z)	 1060 ± 100 MPa 800 ± 100 MPa	 600 ± 50 MPa 600 ± 50 MPa	 1140 ± 50 MPa 1120 ± 80 MPa	 1000 ± 50 MPa 1000 ± 60 MPa
3.	Elongation at break according to [25] - in horizontal direction (XY) - in vertical direction (Z)	 (11 ± 3) % (24 ± 4) %	 min. 20 % min. 20 %	 (7 ± 3) % (10 ± 3) %	 min. 10 % min. 10 %
4.	Modulus of elasticity according to [25] - in horizontal direction (XY) - in vertical direction (Z)	 200 ± 20 GPa 190 ± 20 GPa	 200 ± 20 GPa 200 ± 20 GPa	 110 ± 15 GPa 110 ± 15 GPa	 110 ± 15 GPa 110 ± 15 GPa
5.	Surface roughness	Ra 8 - 12 µm; Rz 38 - 50 µm		Ra 6 - 10 µm, Rz 35 - 40 µm	
6.	Volume rate	1.6...5.5 mm^3/s		5...9 mm^3/s	

built in EOS Titanium Ti-6Al-4V have a chemical composition corresponding to ISO 5832-3, ASTM F1472 and ASTM B348. This well-known light alloy is characterized by excellent mechanical properties and corrosion resistance combined with low specific weight and biocompatibility [15-18]. EOS CobaltChrome MP1 is a fine powder mixture for laser-sintering on EOSINT M 270 systems, which produces parts in a cobalt-chrome-molybdenum-based superalloy. This class of superalloy is characterized by having excellent mechanical properties (strength, hardness etc.), corrosion and high temperature resistance.

The chemical composition of the materials used for prosthetics and medical instruments influence their mechanical properties, biocompatibility and resistance to corrosion in different working environments. The lowest guaranteed values of the mechanical properties for the components obtained by DMLS rapid prototyping process (from titanium and Co-Cr alloy powders) are presented in table 3 [13,14,19-24].

From the comparative analysis of the data presented in table 3, it can be observed that the values of the mechanical properties of the components obtained by sintering the two types of metallic powders are similar. The Titan components have the advantage of much lower masses, advantage given by the low density of the Titan (4.41 g/cm^3), almost half of the density of CoCr powder (8.3 g/cm^3).

Results and discussions

The micrographic images of the samples obtained by DMLS additive manufacturing are presented in figure 1 (Ti6Al4V) and 2 (Co-Cr). After analysing the images it can be seen that the surface of the components contain

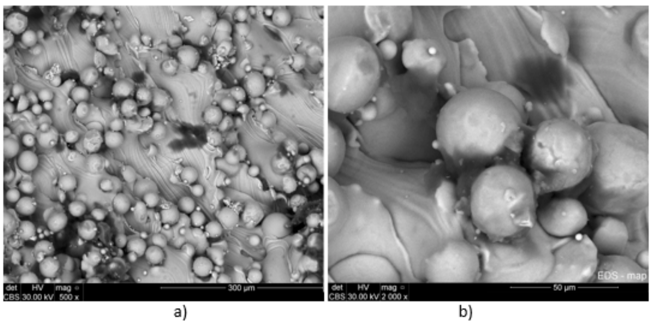

Fig. 1.SEM micrographs of melted EOS Titanium Ti64 alloy powder: a – magnification by 500x; b – magnification by 2000x

incomplete metallic powder melting areas. The dimension and aspect of these areas differ depending on the nature of the powders [26].

In Ti6Al4V powder sintering small grains of melted powder (fig. 1 a,b) that have adhered to the surface of the obtained components can be observed. These grains can be easily removed by polishing the surfaces of the components.

In the components obtained by Co-Cr powder sintering, melted irregularly shaped areas with a larger amount of melted powder grains can be observed (fig. 2 a,b).

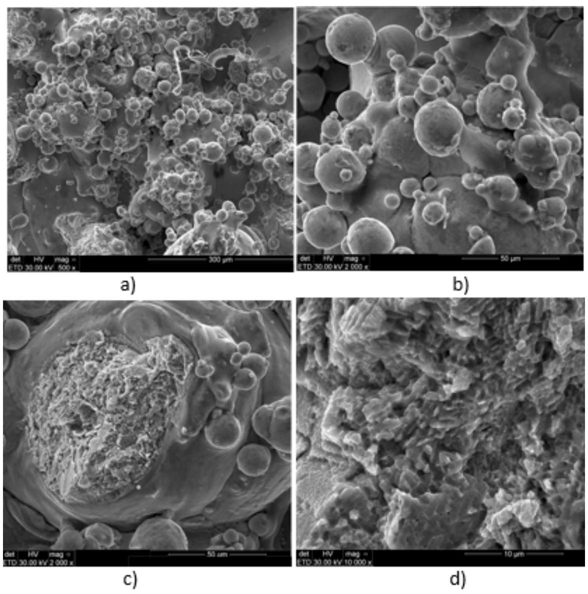

Fig. 2. SEM micrographs of melted EOS CobaltChrome MP1 alloy powder: a – magnification by 500x;
b,c – magnification by 2000x, d – magnification by 10000x,

The thermo physical characteristics of the metallic powders influence the temperature distribution in the melting area. In the case of Co-Cr powder, taking into account the low thermal conductivity, the temperature in the melting area may reach the vaporization temperature of the material, which can lead to the molten metal boiling bath phenomenon. This may lead to the appearance of inhomogeneous areas and rapid solidification areas (fig. 2 c,d).

The overheating of the material in these areas increases the probability of modifying the structure of the material, meaning its aging, having the effect of changing the properties of the obtained components.

Rapid solidification may lead to the increase of the hardness of the material and, in the end, to the occurrence of cracks or pores type nonconformities in the product. These nonconformities lead to the decrease of the bearing capacity of the components obtained by additive manufacturing and, in certain situations, to failure in exploitation.

The local overheating of the components also leads to the increase of internal tensions whose values can exceed the yield strength or, in extreme cases, the value of the tensile strength of the material.

The increase of internal tensions causes the deformation of component which can lead to detaching it from the supports. The occurred deformations and the detachment from the supports influence the manufacturing process. In extreme situations, substantial differences occur between the 3D model of the product and its final shape.

Conclusions

The paper analysed two samples obtained by sintering Co-Cr and Ti6Al4V powders using DMLS additive manufacturing process.

After analysing the results obtained by subjecting the samples obtained by DMLS process we can draw the following conclusions:

The thermo physical properties of the powders used in additive manufacturing influence the mechanical properties of the components as well as the additive manufacturing process.

When using Co-Cr powders it is recommended to change the manufacturing process parameters in order to minimize the thermal energy introduced into the melting zone. This change leads to temperature drop in the working area and reduces the risk of overheating and defects occurrence.

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