MICROSTRUCTURAL AND MECHANICAL CHARACTERIZATION OF CO-CR-MO ALLOY COMPONENTS BUILT BY SELECTIVE LASER MELTING

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A high perspective for additive manufacturing (AM) is the selective laser melting (SLM) for the CoCrMo alloys, a biocompatible alloy, suitable also for other industrial applications. The microstructural characteristics, yield stress, ultimate tensile strength, elongation and micro-hardness of the CoCrMo alloy SLM consolidated samples are evaluated. Microstructural analysis revealed SLM samples with homogeneity of layers and a casting sample with dendritic ramifications. The SLM specimens demonstrate better parameters than casting sample.

Keywords: selective laser melting, CoCrMo, biocompatible alloy, mechanical characterization, microstructural analysis.

1. Introduction

In order to extend Metal Additive Manufacturing (MAM) use, it is necessary to determine the intimacy of process processing and materials characterization and to adjust variability of processing and the structural/ metallographic and mechanical characteristics of built materials [1].

CoCr alloys with Molybdenum (Mo) and/or Tungsten (W) are actually declared as biocompatible and are frequently considered for this purpose in medicine for dental applications and orthopaedic prosthesis. Many concerns are raised in the last years for patients with metal orthopaedic implants that have elevated serum Co and Cr concentrations [3, 4]. However, researches are continuing to develop special CoCrMo alloy powder materials, with low corrosion and high resistance especially for dental purposes and prosthetics material for bones, proving success on biocompatibility analysis and mechanical properties. Consistently, there are other applications for CoCrMo alloys demonstrated in aeronautics, auto, marine engineering, etc.

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The success of the Laser Metal Deposition (LMD) and Laser Powder Bed Fusion (LPBF) is very well-known for MAM of components from CoCrMo alloys. Positive mechanical properties of CoCr alloys including Mo and W elements have been highlighted in the specific literature [1, 2, 4 - 6]. Studies on laser assisted additive manufacturing using Laser Engineered Net Shaping (LENS™) and SLM technologies of CoCrMo alloy demonstrated that high laser power, low powder feed rate, and high scan speed can produce metallic components with excellent mechanical, tribological and electrochemical properties [7 - 9]. CoCrMo alloys have revealed better properties in the SLM samples then casting probes [5].

Testing mechanical properties and microstructural characterization of SLM parts have proved good results using different EPBs (energy power bonding) on the MAM equipment, accordingly on EOS® M270 [8] of 200W and, respectively, on SLM® 280HL of 400W [5].

A high potential of SLM technology is to apply it further in repair and remanufacturing of used components, but many mechanical characteristics and structural aspects must be validated [10].

In the actual paper, we present a research performed for enriching the technological data on AM of parts made of CoCrMo alloy with W content, particularly by LPBF on a new SLM machine.

2. Experimental conditions

Within the research, three types of testing samples, E1, E2, E3, have been designed so that: E1, E2 – to be manufactured by SLM, and E3 – to be obtained from an existing casting knee prosthesis, all from CoCrMo alloy with W content.

The SLM machine was a new Shining EP®-M250, with a water-cooled fiber laser/wavelength of 1060-1090 nm, class IV, 500 W – laser power (Fig. 1), in low Oxigen environment (1000 ppm).

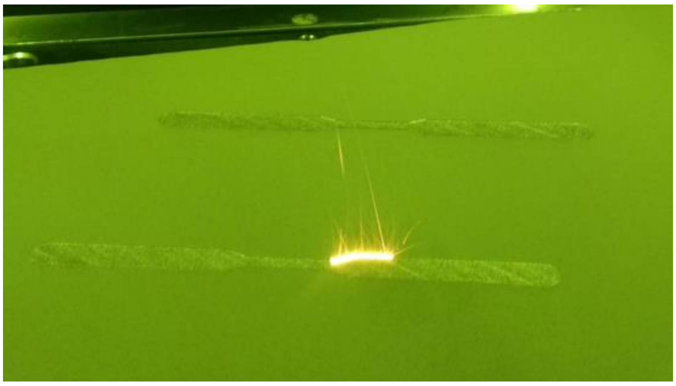


Fig. 1. SLM process using Shining EP®-M250 machine

The basic material for E1 and E2 samples was AMPERPRINT® 0037 CoCrMo alloy powder designed for additive manufacturing by H.C. Starck Company, with particle size range between 15 to 45 µm. The chemical composition of alloy powder is Cr 27 – 30 %, Mo 5 – 7 %, Co 59.4 – 64.4 %, Mn & Si each 1 %, W 0.2 %, Fe 0.75 % and other elements as Al, B, C, N, Ni, O, P, S, Ti 0.01 – 0.25 % (from producer data sheet). All SLM samples were consolidated by heating treatment for 45 minutes at 450°C and at 2 hours at 750°, as suggested by SLM equipment producer.

The tensile strength tests were applied to standard E1 and E2 samples (ASTM E8/E8M) by using an universal hydraulic testing machine Walter & Bai LFV 300 (Fig. 2).

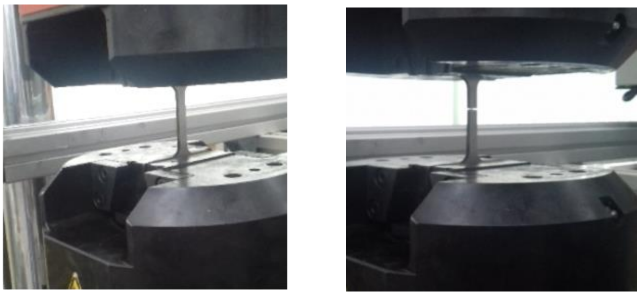
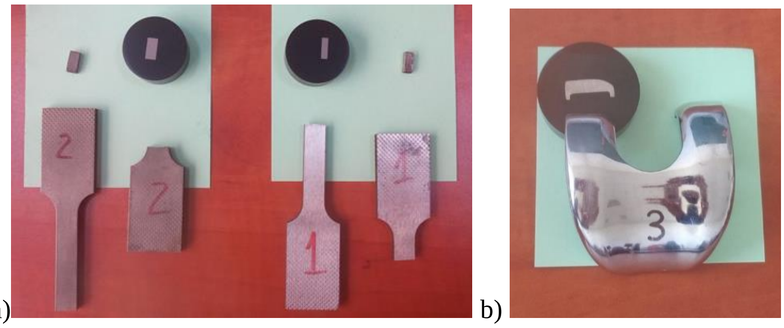


Fig. 2. Tensile strength tests

Data on tensile strength of E3 sample were collected from literature.

The micro-hardness tests were performed for all samples using Vickers hardness with a Shimadzu HMV 2T machine on load 1961 N, for time of 15 s.

The fracture analysis and microstructural properties were performed on consolidated CoCrMo alloys after tensile test. Thus, the fractured parts of tensile test specimens were machined and prepared by mechanical grinding (SiC paper 2000) and by fine polishing (0.02 µm), as presented in Fig. 3: type of SLM sample 1 – E1 at thickness of 4 mm, type of SLM sample 2 – E2 (Fig. 3a) and casting sample 3 - E3 have each the thickness of 5 mm (Fig. 3 b).



a) b)

Fig. 3. a) SLM standard samples b) casting sample

For microstructure characterization, different etching solutions with no reactivity on SLM probes were tested. The specimens E1 and E2 were etched by electrolytic etching solution of 30% HCl with a few drops of H_2O_2, 4V, graphite cathode (15-30 seconds at room temperature). Etching solution for E3 sample was 5 ml HNO_3, 200 ml HCl, 65 g $FeCl_3$.

The microstructural characterization was performed using optical microscope – Olympus GX51 (OM) and scanning electron microscope (SEM - EDS) - Quanta INSPECT F50. Chemical composition was determined with X-Ray diffraction equipment PANanalytical X'pert Pro MPD.

3. Results and discussions

3.1 Mechanical properties

Mechanical properties of E1and E2 samples manufactured by SLM and E3 by casting, respectively, are showed in Table 1, Figs 4 and 5.

Table 1

Mechanical tensile strength values

Mechanical Characteristics (average)	**Samples of CoCrMo alloys**		
	SLM – E1	SLM – E2	Casting – E3
Yield stress [MPa]	1075.2	1246.2	778*
Ultimate Tensile Strength [MPa]	1278	1435	938.36*
Elongation (%)	6.67	4.03	8.3*
Vickers Hardness (HV)	450.6	445.8	429
**Properties collected from literature [14]*			

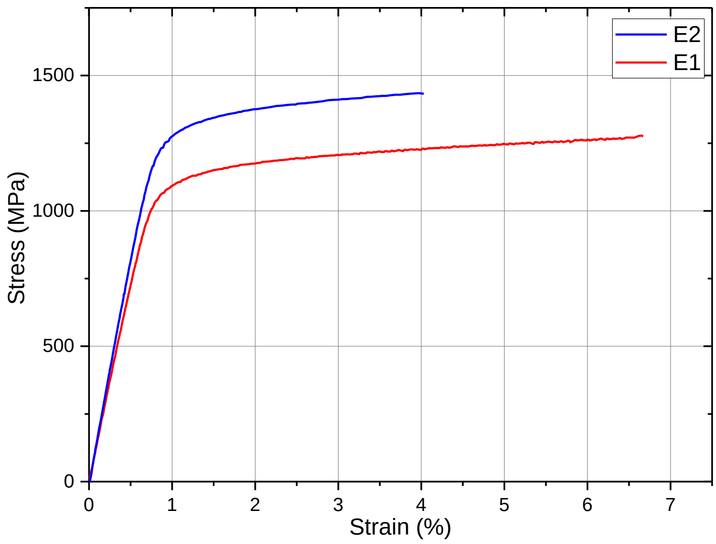


Fig. 4. Tensile test of SLM samples E1-E2

It can be observed that the E3 samples, fabricated by casting, have inferior Yield Stress, Ultimate Tensile Strength and Vickers Hardness compared with SLM parts (Table 1, Fig. 4).

The above results for CoCrMo alloy reveal that the SLM-processed materials show particularly good consistency in their mechanical properties.

For all samples E1, E2 and E3, the micro-hardness was tested five times. The micro-hardness of the SLM samples E1 and E2 are slightly higher than of the E3 casting samples (Table 1, Fig. 5). This is due to a fine homogeneity of SLM sample microstructure, based on very high cohesion of the CoCrMo metallic alloy powder particles.

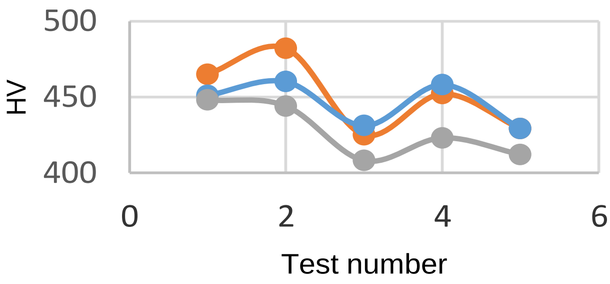


Fig. 5. Vickers hardness for E1, E2, E3 samples

3.2. Microstructural characterization

Microstructural analysis was carried through OM and SEM-EDS. This highlighted a characteristic morphology of SLM specimens with specific ramification described by literature [5, 9], with weld like structure of the laser melting (a) and for casting samples with dendritic arms (b).

(a) (b)

Fig. 6. Images of CoCrMo specimens after chemical etch (black points indicate porous): a) SLM and b) casting samples

Fracture analysis shows a fragile rupture (Fig. 7) and pores presence (width range of 20 - 24 μm and length of 60 μm), besides some small powder particles are evidenced in these pores. SLM presents homogeneous matrix due to the rapid cooling process based on laser melting process.

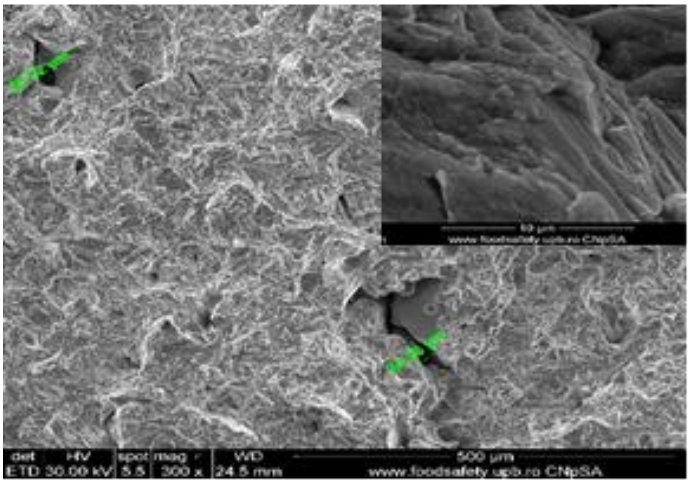


Fig. 7. Fracture analysis for probe E1 (SLM) (500 μm and 10 μm captures)

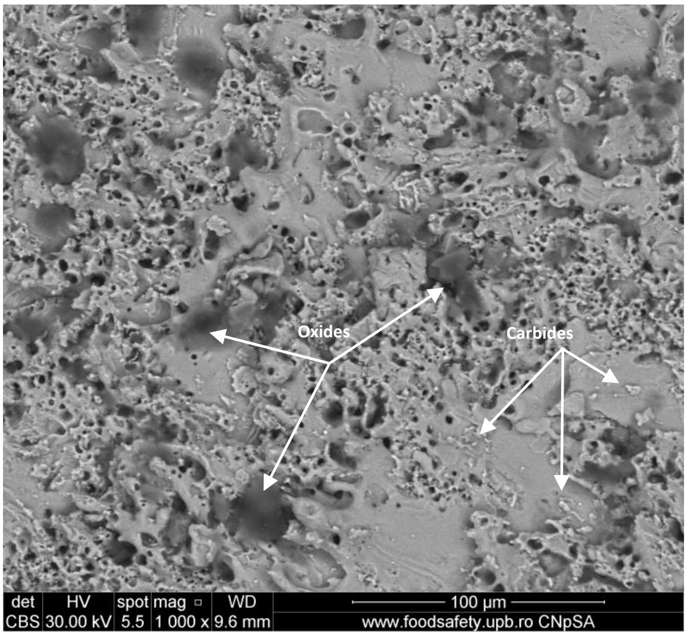


Fig. 8. Black patches indicate the oxides & dark-white the carbides in the CoCr alloy microstructure (100 μm)

On the surface of SLM E1, E2 samples, there are visible carbides and oxides precipitates (Fig. 8).

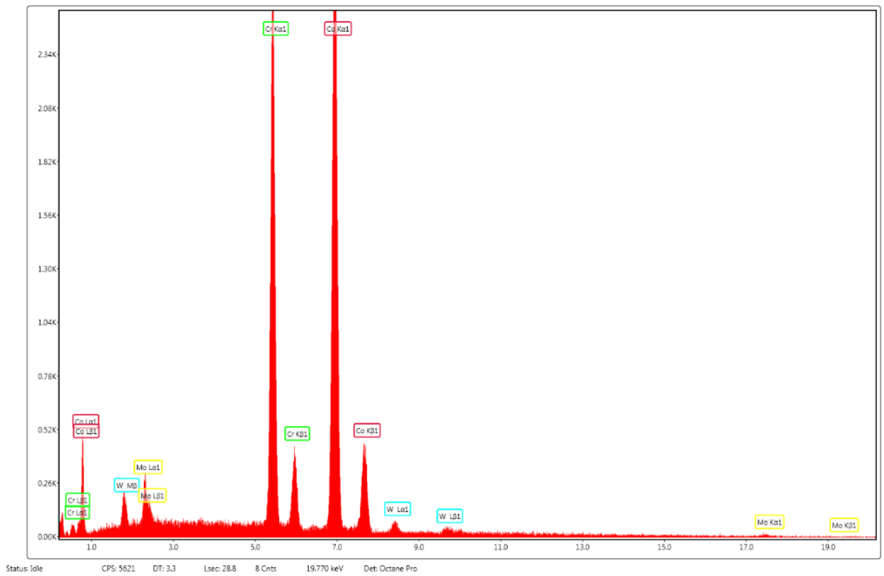
Chemical composition of SLM E1, E2 samples (comparable with producer chemical composition, with small differences due to SLM melting process) and cast E3 sample revealed the specific similarities and differences between CoCrMo alloys tested.

Table 2

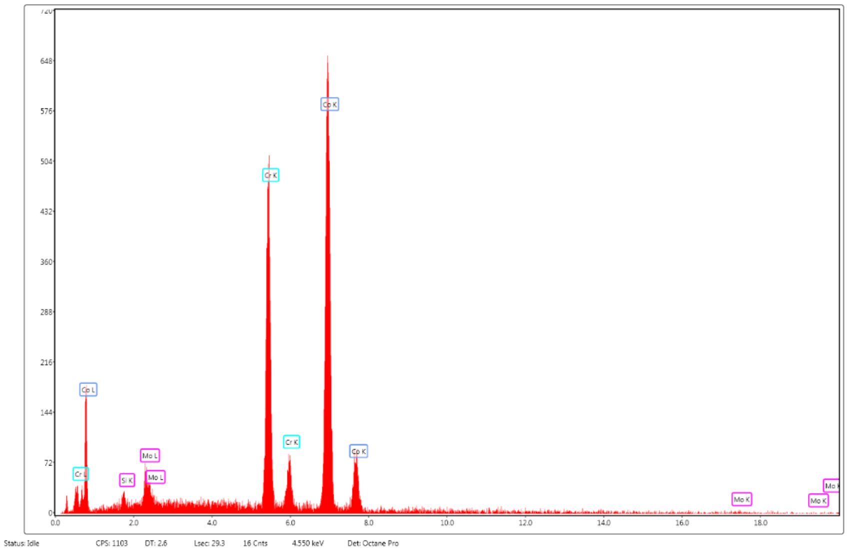
Chemical composition for E1, E2, E3 samples

Element	**Weight of CoCrMo alloys**		
	SLM – E1	SLM – E2	Casting – E3
Cr	27.32	28.07	32.57
Co	54.75	57.19	29.46
Mo	14.98	11.73	18.89
W	2.95	3	-
C	-	-	11.02
O	-	-	6.84

The SLM parts contain W and a consistent quantity of Co, but in case of cast sample E3 the Co content is lower. Moreover, in casting sample the Carbon and Oxygen presence may occur in carbides and oxides precipitates and those can influence the mechanical properties (Table 2 and Fig. 9).



(a)



(b)

Fig. 9. Chemical composition of SLM E1(a) and cast sample E3(b) (revealed by SEM-EDS)

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4. Conclusions

Investigating and analysing mechanical properties and the microstructure of SLM samples by using higher energy laser power (500 W), in low oxygen environment, explain why casting probes showed formation of carbide and oxydes rich in molybdenum and chromium elements. This determines improved chemical and structural homogeny and low porosity of SLM parts if AM process is well settled. Mechanical properties of samples manufactured by SLM are superior to those of casting samples, even if in literature the cast Co-Cr alloy specimens showed the highest Vickers hardness [14].

Considering CoCrMo alloy components as great substituents for casting parts in automotive or aerospace industries, there is needed more specific characteristics to be determined by design flexibility and mechanical properties improvement. Variability of SLM building orientation and design changes are the future of AM research development as well as for repair techniques. However, only after many other experiments we may consider details about the costs and technologies' comparison to clarify the potential of SLM manufacturing opportunities, above presented industries accepting actually only prototypes for testing as are cited [11-14].

Different technical conditions, such as process control and metrics, should be developed in order to improve the precision of MAM, validation and demonstration of the structural integrity of components, energy and material efficiency and post-processing.

All specified challenges represent opportunities for new research regarding MAM technology development, process optimisation, integration, standardisation and societal acceptability.

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