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The Influence of Heat Treatment on the Mechanical Properties of 3D-Printed Cobalt-Chrome Alloy Used in Dental Laboratory Practice

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Abstract
The material used for manufacturing of dental implantation prostheses is cobalt-chromium alloy. The following study presents a new heat treatment technology for dental implantation prostheses. Specimens were created with the innovative technology of 3D printing. The brittleness of specimens subjected to heat treatment with parameters recommended by the manufacturer made it necessary for us to reconsider the heat-treating process. After changing given heat treatment processes, tensile and hardness tests were performed. From these tests, the optimal heat treatment process technology was chosen.

Keywords: *cobalt-chrome alloy, heat treatment, 3D printing.*

1. Introduction

In recent decades, cobalt-chromium alloys have been widely used in casting molds due to their outstanding corrosion resistance, bio-compatibility, and strength [1–3]. Over the years, cobalt-chromium (Co-Cr) alloys have shown remarkable versatility and durability as orthopaedic implant materials [4]. Co-Cr alloys are also used in dental practice e.g. abutments (superstructures), crowns, and bridges [5]. These alloys provide the best balance between mechanical strength and wear resistance. Moreover, their corrosion resistance is also remarkable [6–10]. In the dental field, conventional lost-wax casting techniques have been used for decades. However, these techniques are susceptible to human errors [11]. The production of dental implants is common with conventional methods, for example casting technology [12]. Precision casting and forging still belong to conventional methods in terms of implant manufacturing [13]. On the other hand, additive manufacturing technologies are becoming even more widespread in the production of dental implant prostheses [14]. To make SLM technology suitable for implant or prosthesis manufacturing, certain conditions must be met. The mechanical and chemical properties of the layers created with laser melting of particles must match strict requirements [15]. Mechanical properties and corrosion resistance of alloys processed with SLM (Selective Laser Melting) were studied [16]. Moreover, the strength of the adhesion bond between the ceramic material and Co-Cr alloy was also examined [17].

2. Materials and methods

2.1. Materials used

Type 5, ISO 22674, and ISO 9693-1 dental Co-Cr alloy were used. The chemical composition (% by weight) of cobalt-chromium is shown in **Table 1.**

Table 1. *Chemical composition of Co-Cr alloy*

Element	% by weight
Cobalt (Co)	63.9
Chromium (Cr)	24.7
Tungsten (W)	5.4
Molybdenum (Mo)	5.0
Silicon (Si)	1.0

2.2. 3D printing of specimens

Co63.9Cr24.7W5.4Mo5.0Si1.0 (%) alloy can be the material of choice for implants and pros-theses created with additive manufacturing processes. Test specimens were manufactured with a Sisma Mysint 3D printer. 3D printing is carried out with LMF (Laser Metal Fusion) technology. This technology requires a specific printing strategy. It contains support structures for heat dissipation. A programmable furnace for additional heat treatment was installed nearby the printing unit. Furthermore, a dedicated software and milling machine was available for precision post-processing. Additive manufacturing is preceded by a digital model design. 3D printing is an additive manufacturing technology during which the metal-powder layers are added layer by layer, and the specimens are created with the structured fusion of these layers. The specimen model was designed in a 3D virtual environment and was followed by the printing process that lasted approximately four hours. After printing, specimens are removed from the machine and then separated from the building platform. The heat dissipating support material, which connects the specimens with the disc, is removed afterwards.

2.3. Heat treatment

Following the 3D printing procedure, specimens were subjected to heat treatment with parameters recommended by the manufacturer. **Figure 1.** shows the given heat treatment parameters obtained from the manufacturer. Heat-treating consists of three phases: heating, soaking, and cooling. The proper heat-treating technique is chosen based on the size, geometry, material, and quality requirements of the given part. Hereby, the most important technological parameters can be defined, such as heat-treating temperature and cooling method.

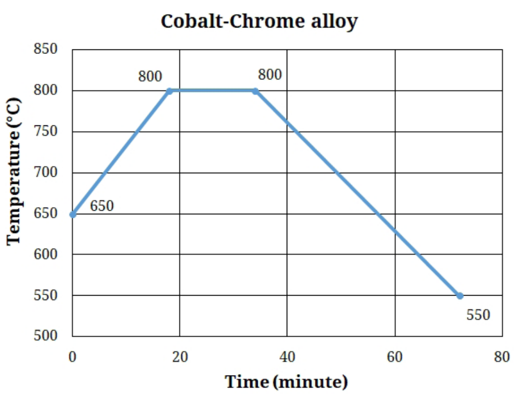

Figure 1. *Heat-treating process provided by the manufacturer*

3. Experiments

Using heat treatment parameters recommended by the manufacturer resulted in a brittle structure, which led to the fracture of some printed specimens. The heat-treating process parameters were changed after this. As a first approach, the heat treating temperature was changed. Numbers in **Table 2** label the following: number 1 indicates the heat treatment process provided by the manufacturer with a maximum temperature of 900°C. Numbers 2 and 4 represent heat-treating processes with a maximum temperature of 900°C. Numbers 3 and 5 mark 1050°C as the maximum temperature. At numbers 3 and 5, process times were changed. Here, all three phases of heat treatment were extended in time.

Changes were determined based on metallographic and experimental data.

Heat treatment marked with number 1 follows manufacturer's recommendations. Based on these experiments, number 4 shows the best solution so far, where fracture strain was increased the most. Thus, elastic modulus decreased, which meant the reduction of the brittleness of the whole structure. **Figure 2.** shows the process diagram for heat treatment labelled with number 4. Number 5 heat treatment had a temperature of 1050°C with a holding time of 118 minutes. No major differences were discovered, but surface oxidation occurred.

AHardness tests were then performed on the specimens. Rockwell hardness was measured in different points of the samples. **Table 3.** shows average hardness values characterizing the specimens.

Table 2. *Mechanical properties obtained after testing*

Number	Tensile strength (Mpa)	Fracture strain (%)	Elastic modulus (Mpa)
1	923	7.4	39 180
2	1041	7.2	47 362
3	1095	7.5	45 302
4	1003	16.06	33 804
5	1097	12.05	34 742

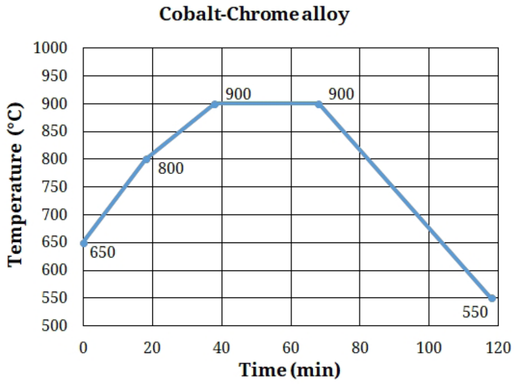

Figure 2. *Heat treatment process*

Table 3. *Mechanical properties measured*

Number	Hardness (HRC)
1	37.37
2	42.3
3	40.04
4	44.88
5	44.4

Table 3. shows the highest average hardness for the specimen marked with number 4. Hardness values measured on specimen number 4 also showed the lowest standard deviation. Other samples showed higher standard deviations during hardness tests. The next step of our research is influenced by the cause of these values.

4. Conclusion

Different heat treatment processes were presented in this study. Our goal was to obtain such mechanical properties for the additively manufactured cobalt-chromium alloy specimens that match dental requirements as precisely as possible. Elastic modulus, which provides information about the stiffness of the material, decreased. The study is going to be continued with the examination of different heat-treating processes. Partial results were achieved.

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The Erdélyi Múzeum-Egyesület as Publisher, and the Editorial Office of Acta Materialia Transylvanica regret to inform the authors and readers that the prefixes of the DOI identifiers of the Hungarian versions of the articles in issues 1 and 2 of the journal in 2018 were incorrectly published.

In the article headings, the DOI prefix corresponding to the Hungarian version of the article is **10.33923**, not 10.2478.

In September 2023, the prefixes were corrected in all articles on the websites of the journal issues:

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and

https://eme.ro/publication-hu/acta-mat/acta2018-2.htm respectively

https://eme.ro/publication/acta-mat/acta2018-2.htm

showing the original incorrect one crossed out and the new, correct identifier.

The replacement of the DOI identifiers with the correct number has also been done in the Hungarian Repository of Scientific Works (MTMT).

We apologize to all authors and readers for this error, and respectfully request that you use the new, correct identifier from now on!

On behalf of the Erdélyi Múzeum-Egyesület Publisher and the Editorial Office of Acta Materialia Transylvanica:

Bitay Enikő

Editor-in Chief

Cluj-Napoca, 1st September, 2023.