DOI: 10.21062/mft.2026.013 © 2026 Manufacturing Technology. All rights reserved. http://www.journalmt.com

# Microstructure and Mechanical Properties of Biomedical Co-Cr-Mo Alloy Produced by Precision Casting and 3D Printing Technologies

Hana Thürlová (0000-0001-7011-5573)*, Dalibor Vojtěch (0000-0002-6910-3206)
Department of Metals and Corrosion Engineering, University of Chemistry and Technology Prague. Technická 5, 166 28 Prague 6. Czech Republic.
* E-mail: thurlovh@vscht

**Cobalt-based alloys are widely used for orthopedic implants due to their excellent mechanical properties and corrosion resistance. Biomedical Co-Cr-Mo alloy, commonly applied in knee replacements, is typically produced by precision casting. However, in cases requiring patient-specific geometries, additive manufacturing technologies, such as Selective Laser Melting (SLM), offer promising alternatives. This study compares the microstructure and mechanical properties of Co-Cr-Mo alloy in the as-cast state and after SLM processing. The SLM-produced samples exhibited a fine, cellular microstructure and superior mechanical strength. Specifically, the printed alloy achieved a yield strength of 688 ± 8 MPa and an ultimate tensile strength of 994 ± 11 MPa, exceeding that of the cast material by about 495 ± 1 MPa. These results demonstrate the potential of SLM technology for manufacturing customized orthopedic implants with improved mechanical properties and dimensional accuracy.**

**Keywords:** Cobalt-based alloys, Mechanical properties, 3D printing, Selective laser melting, Microstructure

## 1 Introduction

Cobalt-based alloys are widely used for orthopedic implants due to their excellent mechanical and tribological properties and also good corrosion resistance [1]. The biomedical alloy Co-Cr-Mo, commonly used in knee replacements, is typically manufactured by precision casting [2]. This technology enables the production of castings with complex geometries with very good surface quality. It consists of several steps, such as the preparation of a meltable model and mold, followed by burnout of the model, after which the actual casting process can take place [3]. For this reason, changing the shape of the casting is very time-consuming.

Nowadays, 3D printing technologies are increasingly used for the production of complex-shaped components. The most frequently used method is Selective Laser Melting (SLM), which involves depositing a layer of powder in a powder bed and then scanning it with a laser in areas where the powder is to be melted. The result is a compact product with the desired geometry, a very fine microstructure, and good mechanical properties [4, 5].

The materials prepared by the two methods differ markedly in both their microstructures and mechanical properties. While the as-cast state is typically characterized by a coarse dendritic structure, the 3D printed material produced by the SLM method exhibits a fine-grained, multi-level microstructure [6, 7]. This refinement in grain size in the 3D printed material is directly associated with its higher hardness and strength. The tensile strength of the printed Co–Cr–Mo alloy is generally reported to range between 900 and 1200 MPa [8-12], whereas in the as-cast state, the strength is considerably lower, approximately 500–600 MPa [10, 13]. Nevertheless, the mechanical properties are strongly influenced by specific processing conditions, such as the cooling rate and individual printing parameters.

This research investigates the potential for partially replacing investment casting with SLM technology in the production of Co-Cr-Mo knee implants. Both technologies offer specific advantages and in special cases, for example, custom-made implants, 3D printing may be more suitable. To evaluate this possibility, an analysis of the microstructure and mechanical properties of both cast and 3D printed Co-Cr-Mo alloy was carried out.

## 2 Experimental Methods

In this work, the properties of Co-28Cr-6Mo alloy, with a chemical composition conforming to the ASTM F75 standard, prepared by precision casting and 3D printing, were compared. For the characterization of the cast state, a real knee implant manufactured by the company Prospon spol. s.r.o. (Kladno, Czech Republic), specifically a femoral implant (see Fig. 1 a) was used, and the 3D printed alloy was prepared by Comtes FHT a.s. (Dobřany, Czech Republic). For the preparation of printed materials, SLM technology was used, employing the AconityTWO device with a 250 W laser and a scanning speed of 1000 mm $s^{-1}$. The printed samples were prepared directly as dogbone-shaped samples for tensile mechanical property testing (see Fig. 1 b).

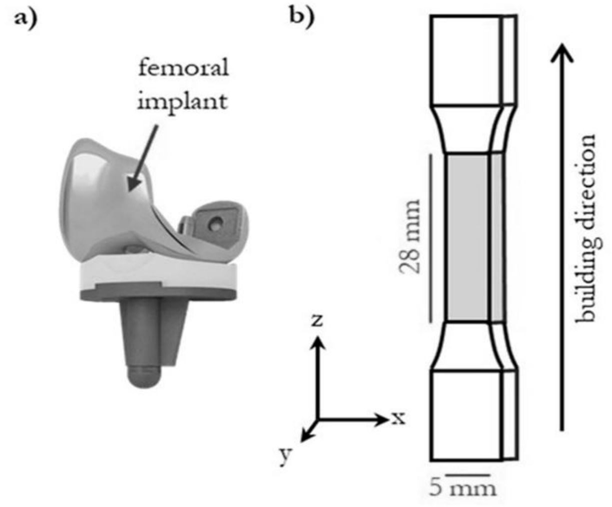

***Fig. 1*** *Total knee implant image (a) and schema of prepared SLM printed samples (b)*

For a comprehensive description of the structure, the phase composition of both samples was determined using X-ray diffraction (XRD) analysis. A PANalytical X'Pert Pro device with a Co cathode ($\lambda = 1.78901 \cdot 10^{-10}$ m) was used for this purpose. Furthermore, the microstructure was observed using an optical microscope (OM, Nikon MA100) and a scanning electron microscope (SEM, Tescan Mira 2) equipped with energy (EDS, Oxford Instruments). Before observation, the samples were polished and then etched in concentrated aqua regia for 2 minutes. To characterize the printed material's microstructure, two samples were prepared – in the XY direction and the XZ direction. The EDS detector was also used for analysis of the chemical composition (see Tab. 1), which met the requirements of the ASTM F75 standard [14].

***Tab. 1*** *Chemical composition of prepared materials (* carbon detection is not quantitatively conclusive using the EDS method)*

| | Concentration [wt.%] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Co | Cr | Mo | Ni | Fe | C | Si | Mn |
| cast | 61.5 | 28.4 | 5.9 | 0.2 | 0.6 | 2.2* | 0.8 | 0.4 |
| SLM printed | 63.4 | 27.5 | 5.8 | - | 0.1 | 3.1* | 0.1 | - |
| ASTM F75 | balance | 27-30 | 5-7 | <0.5 | <0.75 | <0.35 | <1 | <1 |

To determine the mechanical properties, Vickers hardness measurements were first performed under a load of 1 kg for 10 s (EN ISO 6507). A total of 10 measurements were performed and statistically evaluated, including a confidence interval at a 95% significance level. In addition, tensile testing was carried out using an Instron 5882 device. The loading speed, determined according to the standard (EN ISO 6892), was $v = 1.68\ \mathrm{mm \cdot s^{-1}}$. Testing was performed three times for each material.

## 3 Results and Discussion

In terms of phase composition, there were small differences between the materials (Fig. 2 a). While the SLM printed alloy was composed of 70 wt.% fcc phase and 30 wt.% hcp phase, the cast sample also showed the presence of 65 wt.% of fcc phase, 33 wt.% of hcp phase, and 2 wt.% carbides corresponding to Cr23C6. In general, these materials often contain a combination of the majority fcc and minority hcp phases, the content of which is around 25-30% [15]. The proportion of the hcp phase also depends on the cooling rate of the material during production. At lower cooling rates, the phase transformation from the fcc structure to the hcp occurs in a larger proportion [16-19].

The distribution of individual phases in the structure of the cast Co-Cr-Mo alloy can be observed in the microstructure image from optical microscopy (see Fig. 3), where a distinct dendritic structure is evident. While the dendrites are formed by the hcp phase (ε-phase), carbides surrounded by a phase with an fcc crystal lattice (γ-phase) occur in the interdendritic sites. This was determined based on the identification of the phases present by XRD analysis and correlation of these results with previous research on cast Co-Cr-Mo alloy [20, 21]. Thanks to SEM + EDS analysis, the distribution of chemical elements in the carbide particles was determined (see Fig. 3). These results show that it is a mixture of chromium and molybdenum carbides, which is often referred to as mixed carbide $M_{23}C_6$ [22]. Quantification using point analysis did not lead to a more detailed determination of the stoichiometry of carbide particles, however, it confirmed an increased concentration of Cr and Mo (see Tab. 2). Overall, the investigated structure in the cast state corresponded to previous research [15, 20, 23].

In contrast, the Co-Cr-Mo alloy prepared by SLM exhibits a structure typical for 3D printed materials (see Fig. 4). In the XY direction, traces of laser scanning are visible, while in the XZ direction, individual printing layers can be observed in the form of melt pools. So-called epitaxial grains then extend across the melt pools. Upon closer observation with a scanning electron microscope, a fine-grained cellular substructure was visible in both directions, which is created as a result of a high cooling rate and the concentration gradient during solidification [24]. Unlike the as-cast state, no carbide particles were detected. The overall microstructure of SLM printed alloy is also significantly more homogeneous and fine-grained.

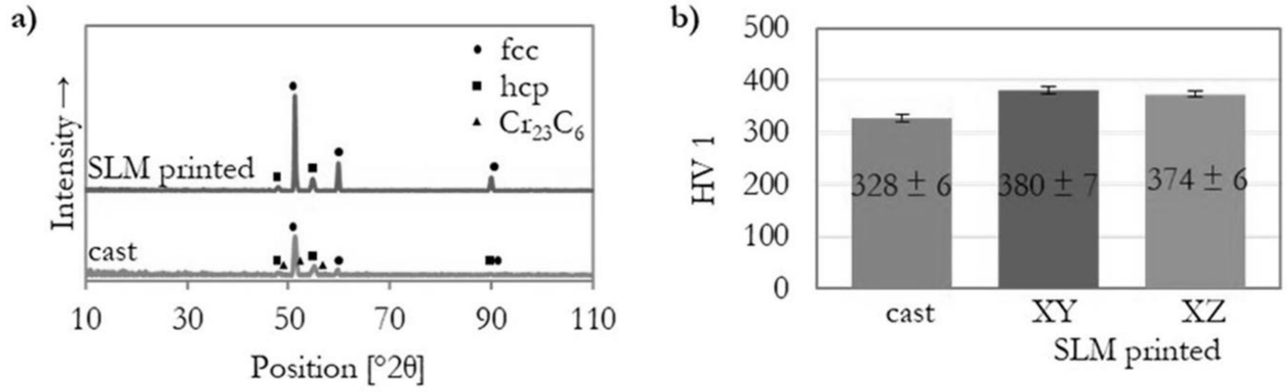

***Fig. 2** Results of phase composition analysis (a) and results of Vickers hardness (b) for cast and SLM printed Co-Cr-Mo alloy*

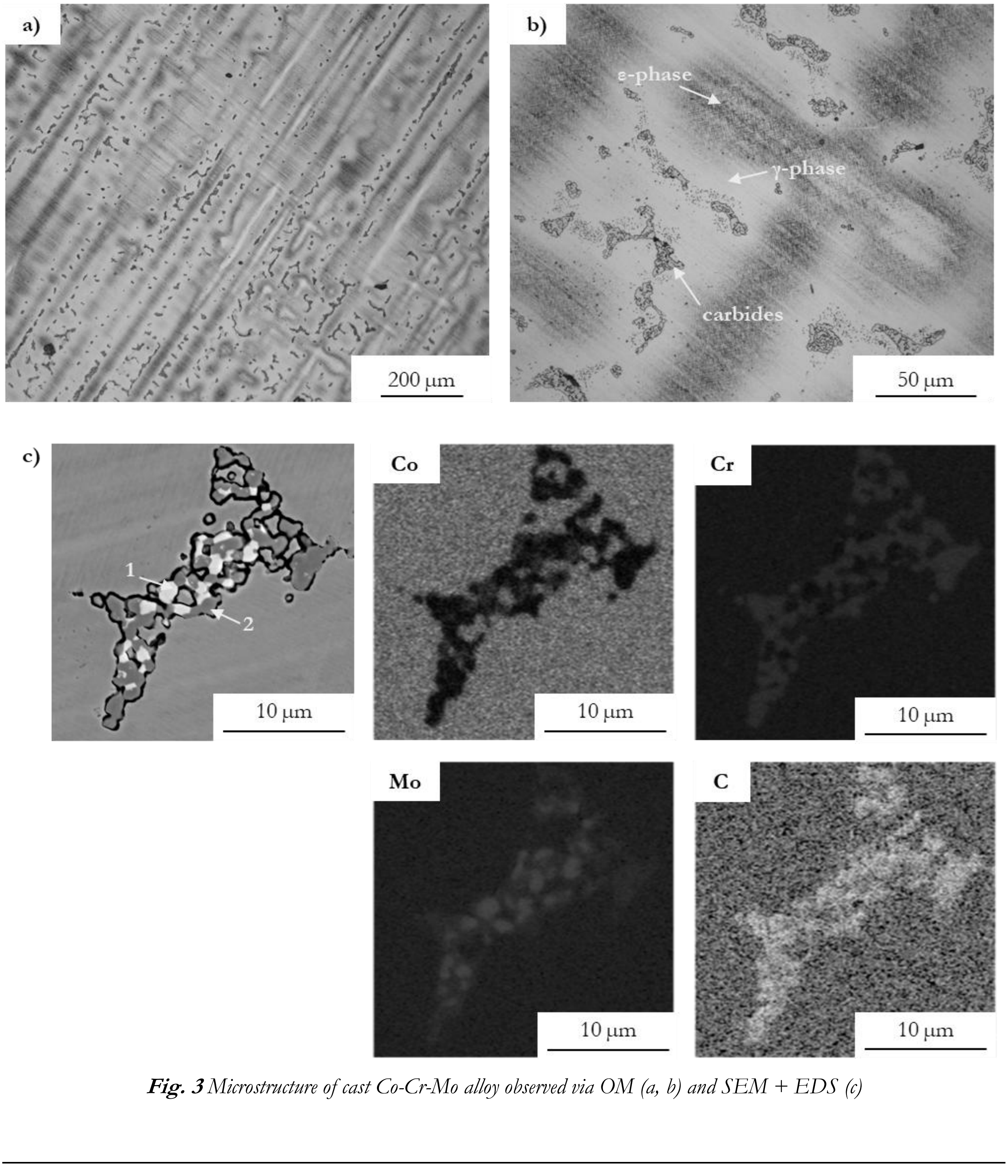

***Fig. 3** Microstructure of cast Co-Cr-Mo alloy observed via OM (a, b) and SEM + EDS (c)*

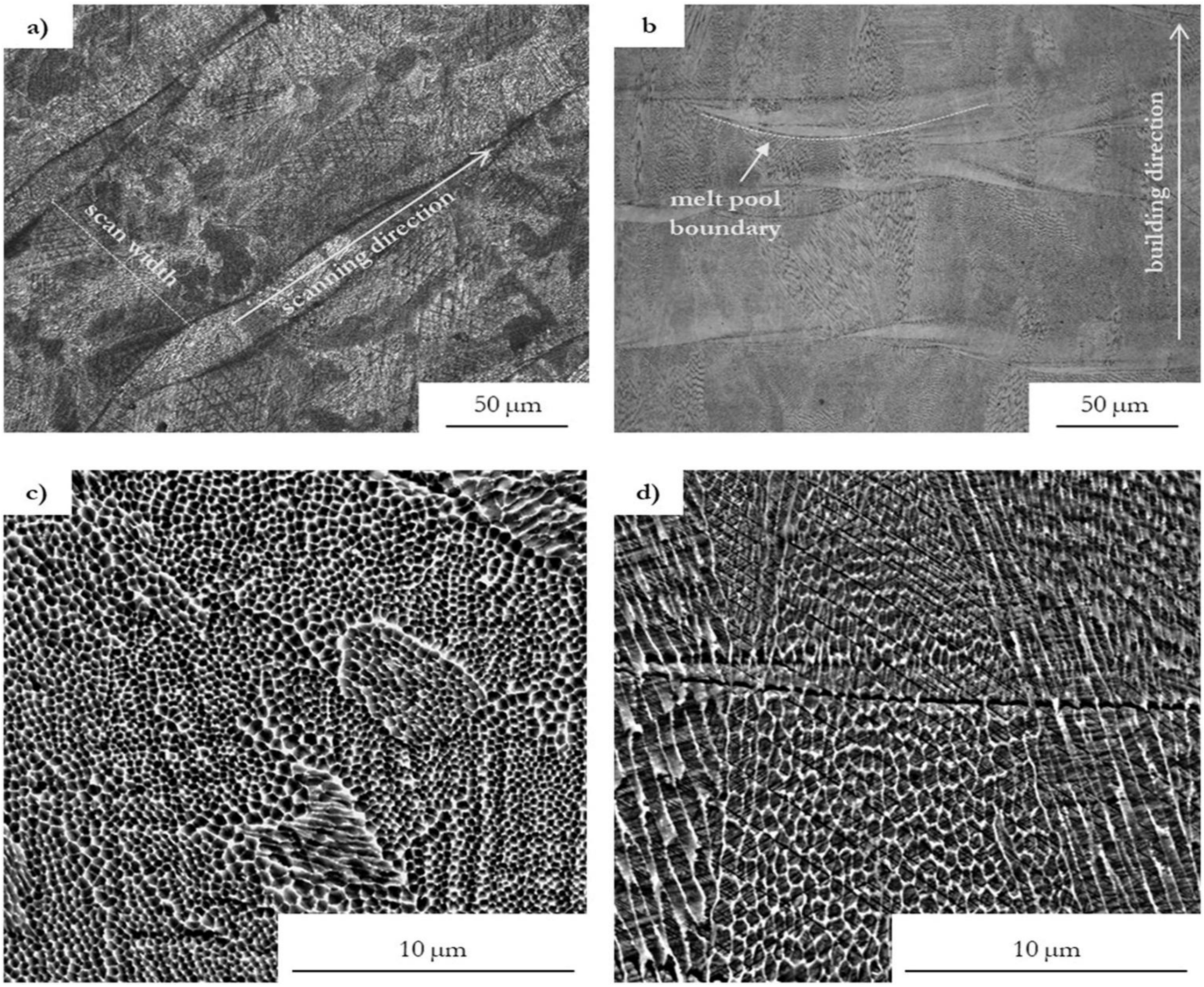

***Fig. 4*** *Microstructure of SLM printed Co-Cr-Mo alloy in XZ direction (a, c) and XY direction (b, d) observed via OM (a, b) and SEM (c, d)*

***Tab. 2*** *Chemical composition from EDS analysis in points marked in Fig. 3*

| | Concentration [at.%] | | | |
|---|---|---|---|---|
| | Co | Cr | Mo | C |
| Point 1 | 21.4 ± 2.1 | 18.6 ± 2.1 | 19.5 ± 1.7 | 35.9 ± 6.2 |
| Point 2 | 10.2 ± 0.6 | 49.2 ± 3.5 | 6.0 ± 0.7 | 34.4 ± 3.4 |

In terms of mechanical properties, the Vickers hardness of the materials was first measured, the results of which are shown in Fig. 2 b. These results show that the cast Co-Cr-Mo alloy showed a lower hardness of 328 ± 6 HV 1 than the alloy prepared by SLM technology. The printed material showed approximately 15% higher hardness in both the XY and XZ directions, with the influence of directionality being very small. It was further found that the SLM printed material prepared in this research showed a higher hardness than reported in the literature for Co-Cr-Mo alloy prepared by sintering technology, which is usually 350 HV [12, 15].

Large differences between the two technologies were also observed in the course of tensile tests (see Fig. 5). The cast sample measured a tensile yield strength of 457 ± 5 MPa and a tensile strength of 494 ± 1 MPa, along with a relatively high ductility of 39 ± 17 %. In contrast, the 3D printed material achieved higher strength, specifically a tensile yield strength of 688 ± 8 MPa and an ultimate tensile strength of 994 ± 11 MPa. Such high mechanical properties are mainly due to the fine-grained structure, which is typical for materials prepared by SLM technology. Despite various preparation conditions, which strongly influence the properties of alloys, most research reports the strength of Co-Cr-Mo alloy in the range of 850-1100 MPa [10, 12, 13, 25]. A large difference can also be observed in terms of ductility, which dropped below 10% in the 3D printed sample. This can also be explained by the high concentration of grain boundaries, which prevent plastic deformation [10]. Overall, the material prepared by SLM technology showed higher strength and hardness, but lower ductility, compared to the as-cast state.

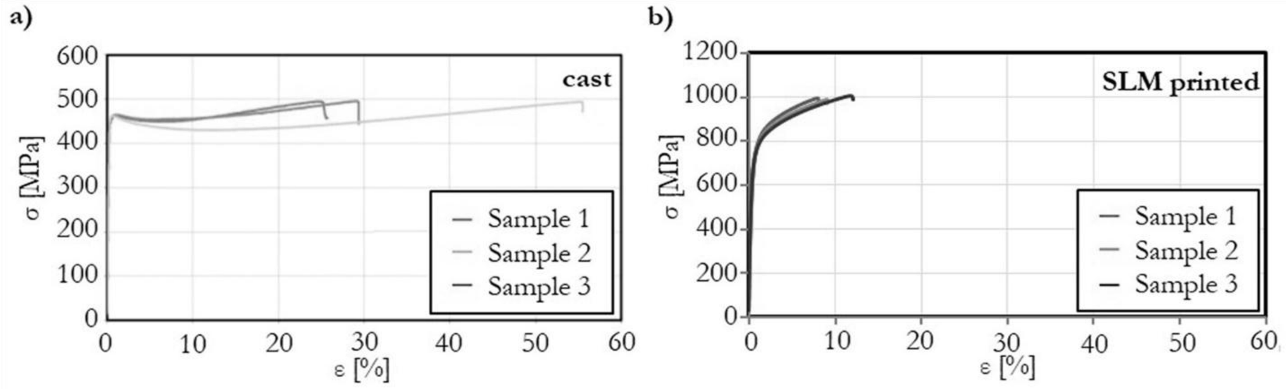

***Fig. 5*** *Tensile stress-strain diagram for cast (a) and SLM printed (b) Co-Cr-Mo alloy*

## 4 Conclusion

This study compares the microstructure and mechanical properties of Co-Cr-Mo alloy prepared by precision casting and SLM technology. While the microstructure of the cast samples was dendritic and contained a large amount of $M_{23}C_6$ carbide particles, the samples produced by the SLM method showed a homogeneous fine-grained cellular microstructure. As a result, the printed samples also exhibited higher mechanical properties, specifically tensile yield strength of 688 ± 8 MPa and an ultimate tensile strength of 994 ± 11 MPa, compared to the as-cast state, which showed values of tensile yield strength of 457 ± 5 MPa and ultimate tensile strength of 495 ± 1 MPa. A similar trend was observed in hardness measurements, where the hardness of the printed material was approximately 15% higher.

The measured mechanical properties were consistent with the values expected from previous research [8-12]. The increased hardness and strength of the 3D printed material indicate its potential for extended service life and reduced wear. However, ensuring sufficient ductility remains essential for its applicability, as inadequate plasticity could lead to premature brittle failure. Ductility can probably be further improved by suitable post-processing treatments [12, 26], which may be the subject of further research. These results demonstrate the significant potential of SLM technology in the production of orthopedic implants, especially with regard to dimensional accuracy and improved mechanical properties.

## Acknowledgement

***This research was financially supported by the Specific university research funding (A1_FCHT_2025_011) and by the project "Mechanical Engineering of Biological and Bioinspired Systems", funded as project No. CZ.02.01.01/00/22_008/0004634 by Programme Johannes Amos Commenius, call Excellent Research.***

## Data Availability

***The data mentioned in the present manuscript are accessible via the Zenodo repository: https://doi.org/10.5281/zenodo.17592298.***

## References

[1] NOVA, K.; NOVAK, P.; KNAISLOVA, A.; DVORSKY, D.; ZYKA, J. 2016. Microstructure of New Cobalt Alloy for Medical Use. *Manufacturing Technology Journal*, 16 (5), 1091-1095.

[2] DOBROVOLNA, L.; VARHANIK, M.; SEDLAK, J.; POLZER, A.; STUDENY, Z. 2021. The design of a device for testing the tribological properties of knee endoprostheses. *Manufacturing Technology Journal, 21* (4), 447-455.

[3] POLI, C. 2001. Chapter 6 - Metal Casting Processes. *Design for Manufacturing*, 115-126.

[4] DUDA, T.; RAGHAVAN, L. V. 2016. 3D Metal Printing Technology. *IFAC-PapersOnLine, 49* (29), 103-110.

[5] MENG, M.; WANG, J.; HUANG, H.; LIU, X.; ZHANG, J.; LI, Z. 2023. 3D printing metal implants in orthopedic surgery: Methods, applications and future prospects. *Journal of Orthopaedic Translation, 42*, 94-112.

[6] VONAVKOVA, I.; VOJTECH, D.; PALOUSEK, D. 2020. Characterization of β-Ti alloy prepared by SLM method. *Manufacturing Technology Journal, 20* (5), 690-696.

[7] FOUSOVA, M.; VOJTECH, D.; FOJT, J. 2016. Microscopic Evaluation of 3D-Printed Materials Surface and Characteristic Microstructure. *Manufacturing Technology Journal, 16* (5), 902-909.

[8] BANG, G. B.; HAN, S. J.; PARK, J. H.; KIM, W. R.; KANG, H.-S.; HYUN, S.-K.; PARK, H.-K.; LEE, T. W.; KIM, H. G. 2024. Effect of heating scan strategy using low energy density on relief of thermal residual stress in L-PBF

process for CoCrMo alloy. *Journal of Materials Research and Technology, 29*, 2720-2731.

[9] LU, Y.; WU, S.; GAN, Y.; LI, J.; ZHAO, C.; ZHUO, D.; LIN, J. 2015. Investigation on the microstructure, mechanical property and corrosion behavior of the selective laser melted CoCrW alloy for dental application. *Materials Science and Engineering: C, 49*, 517-525.

[10] MA, L. Y.; SUN, F. Y.; LI, Y.; YU, H. 2024. Mechanical property, corrosion behavior and cytocompatibility of CoCrMo for dental application: A comparative study of cast and laser powder bed fusion. *Journal of the Mechanical Behavior of Biomedical Materials, 160*, 106788.

[11] PASCO, J.; JIANG, L.; DORIN, T.; KESHAVARZKERMANI, A.; HE, Y.; ARANAS, C. 2024. Phase transformation in additively manufactured Co-Cr-Mo alloy after solution and aging heat treatment. *Materials Characterization, 207*, 113467.

[12] YE, Z.; LI, C.; HUANG, Z.; LUO, H.; CHEN, F.; YAN, Z.; LI, J.; XU, C.; ZHANG, Z. 2022. The effect of solution and aging treatments on the microstructure and mechanical properties of a selective laser melted CoCrMo alloy. *Journal of Materials Science, 57* (11), 6445-6459.

[13] SONG, C.; ZHANG, M.; YANG, Y.; WANG, D.; JIA-KUO, Y. 2018. Morphology and properties of CoCrMo parts fabricated by selective laser melting. *Materials Science and Engineering: A, 713*, 206-213.

[14] FLEMING, T. J.; KAVANAGH, A.; DUGGAN, G. 2020. The effect of melt temperature on the mechanical properties of cast ASTM F75 CoCrMo alloy as explained by nitrogen and oxygen content. *Journal of Materials Research and Technology, 9* (5), 9479-9486.

[15] ROUDNICKA, M.; BIGAS, J.; MOLNAROVA, O.; PALOUSEK, D.; VOJTECH, D. 2021. Different Response of Cast and 3D-Printed Co-Cr-Mo Alloy to Heat Treatment: A Thorough Microstructure Characterization. *Metals, 11* (5).

[16] ROUDNICKÁ, M.; MOLNÁROVÁ, O.; DRAHOKOUPIL, J.; KUBÁSEK, J.; BIGAS, J.; ŠREIBR, V.; PALOUŠEK, D.; VOJTĚCH, D. 2021. Microstructural instability of L-PBF Co-28Cr-6Mo alloy at elevated temperatures. *Additive Manufacturing, 44*, 102025.

[17] TAKAICHI, A.; KAJIMA, Y.; HTAT, H. L.; WAKABAYASHI, N. 2024. Influences of Different Selective Laser Melting Machines on the Microstructures and Mechanical Properties of Co–Cr–Mo Alloys. *Applied Sciences, 14* (15).

[18] TANG, S.; LUZIN, V.; YANG, C.; ZHANG, W.; WANG, Z. 2023. Revealing the macroscale texture in an additive manufactured Co-Cr-Mo alloy by neutron diffraction. *Materials Characterization, 205*, 113243.

[19] KAISER, R.; WILLIAMSON, K.; O'BRIEN, C.; RAMIREZ-GARCIA, S.; BROWNE, D. J. 2013. The influence of cooling conditions on grain size, secondary phase precipitates and mechanical properties of biomedical alloy specimens produced by investment casting. *Journal of the Mechanical Behavior of Biomedical Materials, 24*, 53-63.

[20] ROSENTHAL, R.; CARDOSO, B. R.; BOTT, I. S.; PARANHOS, R. P. R.; CARVALHO, E. A. 2010. Phase characterization in as-cast F-75 Co–Cr–Mo–C alloy. *Journal of Materials Science, 45* (15), 4021-4028.

[21] YAMANAKA, K.; MORI, M.; CHIBA, A. 2015. Assessment of precipitation behavior in dental castings of a Co–Cr–Mo alloy. *Journal of the Mechanical Behavior of Biomedical Materials, 50*, 268-276.

[22] SEDLAČEK, M.; ZUPANČIČ, K.; ŠETINA BATIČ, B.; KOSEC, B.; ZORC, M.; NAGODE, A. 2023. Influence of Precipitation Hardening on the Mechanical Properties of Co-Cr-Mo and Co-Cr-W-Mo Dental Alloys. *Metals, 13* (3).

[23] DA SILVA, D. J.; CONTIERI, R.; CREMASCO, A.; FLORIANO, R. 2022. The Effect of Cooling Rate on the Microstructure and Hardness of As-Cast Co-28Cr-6Mo Alloy Used as Biomedical Knee Implant. *International Journal of Metalcasting, 16* (4), 2187-2198.

[24] PRASHANTH, K. G.; ECKERT, J. 2017. Formation of metastable cellular microstructures in selective laser melted alloys. *Journal of Alloys and Compounds, 707*, 27-34.

[25] ROUDNICKÁ, M.; KUBÁSEK, J.; PANTĚLEJEV, L.; MOLNÁROVÁ, O.; BIGAS, J.; DRAHOKOUPIL, J.; PALOUŠEK, D.; VOJTĚCH, D. 2021. Heat treatment of laser powder-bed-fused Co–28Cr–6Mo alloy to remove its microstructural instability by massive FCC→HCP transformation. *Additive Manufacturing, 47*, 102265.

[26] LU, Y.; WU, S.; GAN, Y.; ZHANG, S.; GUO, S.; LIN, J.; LIN, J. 2016. Microstructure, mechanical property and metal release of As-SLM CoCrW alloy under different solution treatment conditions. *Journal of the Mechanical Behavior of Biomedical Materials, 55*, 179-190.