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Comparative Evaluation of Vickers Hardness in Cobalt-Chromium Alloys Fabricated by Three Different Manufacturing Techniques

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Abstract

Cobalt-chromium (Co-Cr) alloys are widely used in PFM restorations due to their favorable mechanical properties and biocompatibility. With the advancement of contemporary manufacturing technologies, new fabrication methods have been introduced, which may influence the structure and hardness of the material.

Aim. The aim of the present study is to compare the Vickers hardness number of a cobalt-chromium alloy produced using three different manufacturing technologies.

Materials and Methods. A total of 15 specimens made of Co-Cr alloy, measuring 8 mm in width and 4 mm in height, were fabricated and divided into three groups (n = 5) according to the manufacturing technique used: casting, 3D printing, and milling. All samples were standardized in terms of shape and size and subjected to identical surface treatment. Vickers hardness testing was performed under standard conditions with a specified load and dwell time. The obtained results were statistically analyzed (IBM SPSS Statistics 26, Excel 2015, and EdrawMax 7).

Results. Statistically significant differences in Vickers hardness values were observed among the studied groups. The highest hardness values were recorded for the printed specimens, followed by those produced by milling, while the lowest values were observed in the cast samples. The observed differences can be explained by variations in microstructure and the specific characteristics of the manufacturing processes.

Conclusion. The manufacturing technology has a significant impact on the Vickers hardness number of cobalt-chromium alloys. Modern digital methods such as milling and 3D printing demonstrate superior mechanical properties compared to conventional casting, which may be of importance for the clinical application of PFM restorations.

Keywords: Co-Cr alloys, Vickers hardness, casting, 3D printing, milling

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Introduction

Cobalt-chromium (Co-Cr) alloys are widely used in contemporary dentistry, particularly in the fabrication of PFM restorations, due to their favorable mechanical properties, high corrosion resistance, and good biocompatibility. They are characterized by high strength, a high modulus of elasticity, and excellent wear resistance, making them suitable for long-term prosthetic restorations. In addition, Co-Cr alloys demonstrate good resistance to high temperatures and stability during ceramic firing, which is essential for PFM applications (1, 11).

Traditionally, the fabrication of metal frameworks in dental laboratories has been performed using the lost-wax casting technique. Despite its widespread use, this method is associated with several limitations, including the potential formation of porosities, non-uniform microstructure, and process-induced defects, all of which may adversely affect the mechanical properties of the final product. However, with technological advancements, this approach has been increasingly supplemented and in some cases replaced by modern digital methods such as CAD/CAM milling and additive manufacturing (4, 11).

CAD/CAM milling enables the fabrication of restorations from industrially produced blocks with strictly controlled homogeneity and minimal internal defects. On the other hand, additive technologies such as selective laser melting (SLM) allow the production of complex geometries and result in a specific, often finer microstructure characterized by high density and improved mechanical properties.

Different manufacturing technologies have a significant influence on the microstructure of Co-Cr alloys, which in turn leads to variations in their mechanical characteristics. These differences are of particular importance in clinical applications, as they may affect the longevity, wear resistance, and behavior of the restorations under functional loading (9)

Hardness is a key parameter for evaluating the mechanical properties of dental alloys, as it is directly related to the material's resistance to deformation and wear. The Vickers method is widely used for determining microhardness, allowing reliable comparison between different materials and manufacturing techniques.

Despite the extensive use of Co-Cr alloys, there remains a need for further comparative studies to assess the influence of different manufacturing technologies on their mechanical properties, particularly in the context of the increasing adoption of digital methods in dental practice (9).

Aim

The aim of the present study is to compare the Vickers hardness of a cobalt-chromium alloy produced using three different manufacturing technologies.

Materials and Methods

A total of 15 test samples with 8 mm in width and 4 mm in height were prepared. They were divided into three groups, based on the fabrication method.

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Method for casting: The cast specimens were produced using a cobalt–chromium alloy, Remanium® Star (Dentaurum, Germany), specifically developed for metal–ceramic restorations. The alloy exhibits favorable properties for fixed prosthodontic applications, including high biocompatibility, a low coefficient of thermal expansion, and excellent compatibility with dental ceramics. Its chemical composition comprises 60.5 wt.% Co, 28.0 wt.% Cr, 9.0 wt.% W, and 1.5 wt.% Si, with trace amounts (<1 wt.%) of Mn, N, and Nb. The alloy is free from nickel, beryllium, cadmium, and iron, contributing to its high corrosion resistance, biocompatibility, and reduced allergenic potential.
Method for milling: The CAD/CAM-milled specimens were manufactured from a cobalt–chromium alloy, Remanium® Star MD II (Dentaurum, Germany). This alloy has been specifically developed for metal–ceramic restorations and fulfills the requirements of DIN EN ISO 22674 (Type 3) and DIN EN ISO 9693. Its chemical composition comprises 60.5 wt.% Co, 28.0 wt.% Cr, 9.0 wt.% W, and 1.5 wt.% Si, with trace amounts (<1 wt.%) of Mn, N, and Nb. The alloy is free from nickel, beryllium, cadmium, and iron. Its physicochemical properties and coefficient of thermal expansion ensure compatibility with veneering dental ceramics, making it suitable for metal–ceramic applications.
Method for printing: The additive manufacturing specimens were fabricated using a cobalt–chromium alloy powder, Remanium® Star Powder (Dentaurum, Germany), intended for the production of metal–ceramic restorations by means of Selective Laser Melting (SLM) technology. Its chemical composition comprises 60.5 wt.% Co, 28.0 wt.% Cr, 9.0 wt.% W, and 1.5 wt.% Si, with trace amounts (<1 wt.%) of Mn, N, and Nb. The alloy is free from nickel, beryllium, cadmium, and iron. This material is classified as a dental Co–Cr alloy suitable for fixed prosthetic applications and exhibits high dimensional accuracy and favorable mechanical properties.
Each specimen from each group was tested at three different points using the Vickers hardness method.
The determination of hardness was carried out on a ZHV μ-M stand (Zwick/Roell, England) (Fig. 1) under the following test conditions:
Applied force - 2 kgf
Duration of impact - 30 s
Number of measurements per test sample - 3

Figure 1. ZHV μ-M stand (Zwick/Roell, England)

When selecting the measurement point, the requirements for sufficient spacing between the indentations and from the edge of the test samples were followed. During the experimental measurements, the symmetry of the arms of the visible optical cross was also monitored.

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The statistical methods used in the present study included:

- Descriptive statistics:
- Mean value (average) - a measure of central tendency;
- Standard deviation (SD) - a measure of data dispersion;
- Absolute frequency (N) - a measure of the number of observations;

Inferential statistics (hypothesis testing):

- Analysis of Variance (ANOVA) – a parametric test used to assess differences among k independent groups;
- Post-hoc test based on the Least Significant Difference (LSD) to determine between which of the k independent groups statistically significant differences exist.

The null hypothesis states that different manufacturing methods do not result in differences in hardness.

Results

The results are focused on whether there is a difference in Vickers hardness among the following three manufacturing methods: CASTED, MILLING, and PRINTED. For this purpose, 3 groups of 5 samples each are tested at 3 points (Fig. 2).
The highest mean hardness value was observed for the PRINTED group (440 kgf/mm²), followed by the MILLING group (330 kgf/mm²), while the lowest value was recorded for the CASTED group (302 kgf/mm²). Regarding the variability of the results, the CASTED group exhibited the lowest standard deviation (12 kgf/mm²), indicating greater homogeneity of the measurements. The greatest variability was observed in the MILLING group (29 kgf/mm²), whereas the PRINTED group showed a standard deviation of 23 kgf/mm².
The overall mean hardness value for all observations was 357 kgf/mm². Only the PRINTED group exceeded this overall mean value, while the CASTED and MILLING groups remained below it.

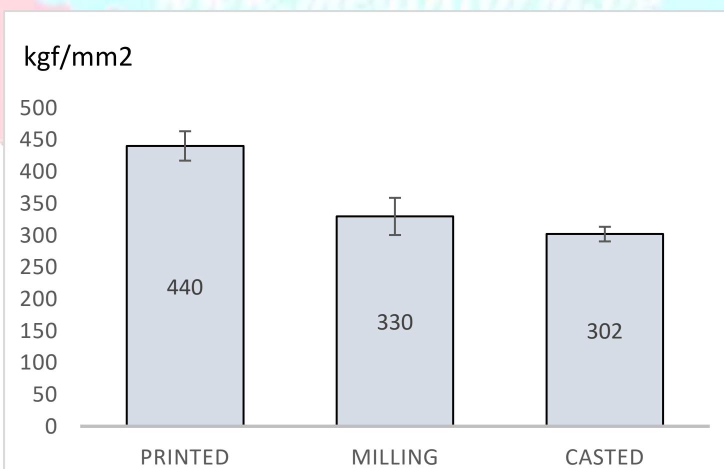

Figure 2. Vickers hardness values for the three manufacturing methods

To identify the specific differences among the groups, a post-hoc analysis was performed. The results revealed statistically significant differences among all three manufacturing methods. The highest hardness values were recorded for the PRINTED group, followed by the MILLING group, whereas the CASTED group exhibited statistically significantly lower hardness values than the other two groups (Table 1).

Table 1. Results of the analysis of differences in Vickers hardness among the CASTED, MILLING, and PRINTED methods

Experimental group / Measured parameter	Propertis	Tested methods		
		PRINTED	**MILLING**	**CASTED**
Vickers hardness	Mean	440 ^{A}	330 ^{B}	302 ^{C}
	SD	± 23	± 29	± 12
	N	15	15	15
ANOVA test	**P-value**	**p<0.001**		

Groups sharing the same superscript letter do not exhibit a statistically significant difference.

The level of significance obtained from the analysis ($p < 0.001$) was lower than the predetermined significance level of $\alpha = 0.05$. Therefore, the null hypothesis was rejected, and the alternative hypothesis was accepted, indicating that the manufacturing method has a statistically significant effect on Vickers hardness.
These conclusions are supported with a confidence level of 95%.

Discussion

The results of the present study demonstrated that the manufacturing method has a statistically significant influence on the Vickers hardness of Co-Cr alloys, leading to the rejection of the null hypothesis. The cast specimens exhibited significantly lower hardness values compared to the milled and additively manufactured groups, other researchers such as Jabbari et al. and Kim et al. have reached similar conclusions (3, 11).
It is well established that conventional casting techniques may result in microstructural defects such as porosity, dendritic grain structures, and elemental segregation, which negatively affect mechanical properties. These structural irregularities reduce hardness and overall material performance, as reported in multiple studies on dental Co-Cr alloys (10, 18).
In contrast, CAD/CAM milling produces restorations from industrially manufactured blocks with highly controlled composition and homogeneity. This leads to reduced internal defects and improved mechanical consistency. Studies have shown that milled Co-Cr alloys exhibit superior and more stable mechanical properties compared to cast alloys due to their refined and uniform microstructure (11).

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Additive manufacturing technologies such as selective laser melting (SLM) have been extensively investigated in recent years due to their ability to produce dense structures with favorable mechanical and microstructural characteristics (11). The findings of the present study, showing comparable hardness between the PRINTED and MILLING groups, are in agreement with previous research indicating that SLM-produced Co-Cr alloys can achieve mechanical properties similar to or superior to those of milled materials (14)

This can be explained by the rapid heating and cooling cycles inherent in the SLM process, which promote grain refinement, reduced porosity, and the formation of a dense microstructure. These characteristics contribute to increased hardness and strength of the material (16, 17).

Furthermore, experimental studies have demonstrated that SLM-fabricated Co-Cr alloys exhibit higher hardness values compared to cast alloys (e.g., approximately 382 HV vs. 335 HV), confirming the superior mechanical performance of additively manufactured materials (2).

The absence of a statistically significant difference between milling and 3D printing observed in this study suggests that both modern digital manufacturing methods are capable of producing Co-Cr alloys with comparable mechanical properties. Similar conclusions have been reported in recent investigations comparing casting, milling, and additive manufacturing techniques (5–7).

However, the slightly higher variability observed in the PRINTED group may be attributed to process-dependent parameters such as laser energy density, scanning speed, and layer thickness, which are known to influence microstructure and hardness in SLM-produced alloys (13).

From a clinical perspective, increased hardness is associated with improved wear resistance and durability of prosthetic restorations (8). Nevertheless, excessively high hardness may complicate clinical adjustments and finishing procedures. Therefore, the choice of manufacturing method should consider both mechanical performance and clinical handling characteristics (12).

The present study has several limitations. The relatively small sample size may limit the generalizability of the results. Additionally, only hardness was evaluated, while other important mechanical properties such as tensile strength, fatigue resistance, and corrosion behavior were not assessed. Future studies should include a broader range of tests and investigate long-term clinical performance.

Studies have shown that Vickers hardness values in Co-Cr alloys vary depending on the manufacturing technology used, with higher values often observed in additively manufactured specimens compared to cast ones. (15)

Conclusion

Within the limitations of the present study, it can be concluded that the manufacturing method has a significant effect on the Vickers hardness of cobalt–chromium (Co-Cr) alloys.

The lowest hardness values were observed in the cast specimens, whereas both additively manufactured and milled samples exhibited significantly higher hardness. The statistically significant difference established between the milled and 3D-printed specimens indicates that the manufacturing technology used has a substantial influence on the hardness of Co-Cr alloys. The specimens produced by selective laser melting (SLM) showed the highest hardness values, suggesting better mechanical characteristics compared with the milled and conventionally cast alloys.

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These findings suggest that modern digital fabrication methods, such as CAD/CAM milling and additive manufacturing, can produce Co-Cr alloys with superior mechanical properties compared to conventional casting. This may have important clinical implications, particularly in improving the wear resistance and longevity of PFM restorations.
However, further studies are required to evaluate additional mechanical and biological properties, as well as long-term clinical performance, in order to fully assess the suitability of these manufacturing methods in dental practice.

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