



## Effect of molybdenum disulfide addition on the flexure and hardness resistance of cobalt-chromium dental alloys

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### ABSTRACT

Dental prostheses are an essential component of restorative dentistry, enhancing not only function but also aesthetics and oral health. Cobalt-chromium (Co-Cr) alloys are among the materials commonly used for dental frameworks, primarily due to their corrosion resistance and high mechanical strength. This study examined the effects of integrating molybdenum disulfide (MoS<sub>2</sub>) at different concentrations (0%wt, 6%wt, and 8%wt) on the mechanical properties and corrosion resistance of Co-Cr dental alloys. It fabricated 90 specimens (30 per group) and assessed their compressive strength, hardness, and corrosion resistance. Incorporating MoS<sub>2</sub> markedly improved the mechanical characteristics of the Co-Cr alloy. Compressive strength and hardness differed significantly across groups ( $p < 0.05$ ). They were greatest in the 8%wt MoS<sub>2</sub> group (141.3 MPa and 912.1 IU, respectively), followed by the 6%wt MoS<sub>2</sub> group (131 MPa and 693.6 IU), and smallest in the 0%wt MoS<sub>2</sub> group (87.72 MPa and 595.3 IU). Corrosion resistance increased with the MoS<sub>2</sub> concentration and was greatest in the 8%wt MoS<sub>2</sub> group. The presence of Mo facilitated the development of a protective oxide layer, thereby reducing corrosion. Our findings indicate that incorporating MoS<sub>2</sub> into Co-Cr dental alloys can improve mechanical strength, durability, and corrosion resistance. Such improvements may result in longer-lasting, more durable dental prostheses, benefiting both practitioners and patients. Future research should focus on the long-term clinical performance and biocompatibility of MoS<sub>2</sub>-enhanced Co-Cr alloys to confirm their use in dental prostheses.

### 1. Introduction

Dental prostheses restore function, aesthetics, and oral health by replacing missing teeth. Cobalt-chromium (Co-Cr) alloys are common due to their strength and corrosion resistance. Removable partial dentures (RPDs) are popular for their affordability [1]. The goal of denture repair is to restore strength and durability [2]. Different prosthesis types suit varying degrees of tooth loss. Dental implants are increasingly used for complete edentulism, driving advancements in implant dentistry [3]. Surgical and restorative processes are becoming more predictable with tools like CT scans and guided surgery [4].

The base of the denture is largely responsible for providing the prosthesis with retention, stability, and support by being closely adapted to the oral mucosa. However; the process of bone resorption is irreversible and may lead to an inadequate fit of the prosthesis; this can be overcome by relining [5].

Acrylic resin is not an optimal biomaterial due to its insufficient impact strength and fatigue resistance. Factors such as biting forces, temperature fluctuations, exposure to saliva, water, acidic meals, and mechanical impacts might contribute to the deterioration of the denture base over time [6]. Porcelain, resin, and metal alloys, including cobalt-chromium (Co-Cr), are commonly used materials, each with distinct advantages and disadvantages. The selection of materials influences prostheses' durability and functionality, as well as patients' comfort and acceptance in their daily lives [7]. Traditional casting, commonly called lost-wax casting, has been the primary method for manufacturing metallic dental restorations for over 70 years. It involves attaching a sprue pin to the wax pattern, which serves as the mold of the specimen, followed by pouring the investment material into the mold [8]. Molybdenum (Mo) is part of the periodic table's VIb series, which also includes

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chromium with tungsten. Mo does not occur naturally in its elemental metallic form; instead, it is found in conjunction with other elements. Molybdenum disulfide ( $\text{MoS}_2$ ) is a hexagonal lattice of two sulfur (S) atoms and one Mo atom. The unique arrangement of atoms in  $\text{MoS}_2$  results in distinct physical and chemical capabilities. In  $\text{MoS}_2$ , each layer is comprised of a single Mo atom sandwiched between two layers of sulfur atoms held together by covalent solid bonds; however, the pi-bonding between layers appears to be more delocalized and exhibits weak van der Waals interactions. The layered structure enables the simple exfoliation of the material into thin sheets. Therefore, it is commonly used as a protective material coating and in composites [9]. In general, the study of transition metal-containing compounds is of significant importance due to their broad applications in fields such as catalysis, energy storage, and advanced structural materials [10-12]. This study examined the effects of integrating molybdenum disulfide ( $\text{MoS}_2$ ) at different concentrations (0%wt, 6%wt, and 8%wt) on the mechanical properties and corrosion resistance of Co-Cr dental alloys. It fabricated 90 specimens (30 per group) and assessed their compressive strength, hardness, and corrosion resistance.

## 2. Materials and Methods

### 2.1. Specimen fabrication

This study fabricated 90 specimens from Co-Cr alloy (Dentify GmbH, Engen, Germany) with different  $\text{MoS}_2$  concentrations (30 per concentration): 0%, 6%, and 8%. Then, the fabricated specimens were divided equally among three tests (30 per test [10 per concentration]): corrosion, hardness, and compressive strength. The Autodesk Fusion 360 program was used to create three-dimensional geometric shapes based on the specified dimensions for each material employed in this study. The STL files containing the dimensions of the Co-Cr specimens were exported to the computer-aided manufacturing (CAM) program for milling with wax castable material. After milling, the sprues were excised from the wax specimens and refined using silicon burs to achieve a polished and smooth surface (Figure 1). Takahashi et al. proposed that specimens are attached to the crucible former using sprue wax. Phosphate-bonded casting investment powder was utilized as a casting material. Initially, 100 mL of liquid was prepared by combining 60 mL of investment liquid with 40 mL of distilled water at a 3:2 ratio. Next, this mixture was placed into the mixer bowl, followed by the addition of 500 g of investment powder. Then, the mixture was hand-mixed using a spatula for 30 seconds to ensure complete wetting of all investment particles.

Next, the bowl was secured to the mixer and mixed for one minute at 350 rpm under vacuum, adhering to the

manufacturer's instructions to prevent any entrapment of air bubbles during the mixing process.



**Fig. 1.** Materials used in the experimental procedure, including molybdenum disulfide ( $\text{MoS}_2$ ) powder (XF NANO, China), wax patterns for compression test (cylindrical), and flexural test (bar-shaped), prepared prior to casting with Co-Cr alloy.

Then, the crucible former was allowed to set for one hour. Once the investment material was fully set, the rubber ring was removed to release the mold, which was then placed into a burnout chamber at room temperature, and the furnace temperature was gradually increased to 400°C. The mold was kept at 400°C for 30 minutes, and then the temperature was slowly increased to 900°C and held there for 45 minutes. This procedure was followed to ensure a complete burnout of the wax-castable material without any residue, per the manufacturer's instructions (Figure 2). Following the complete burnout of the castable material and achieving the target internal temperature, the mold was removed from the furnace and promptly placed on the casting machine. Next, a Co-Cr shot was heated with a high-intensity flame torch until it reached 1300°C and was fully melted, per the manufacturer's instructions. Then, the material's weight was accurately measured with a digital balance to determine the appropriate quantity of  $\text{MoS}_2$ .



**Fig. 2.** High-temperature electric furnace during the burnout stage of investment mold preparation, showing a recorded temperature of 867°C.

Next, the material was ground in a ceramic furnace at 1000°C. Then, the specified quantity of MoS<sub>2</sub> was incorporated into the molten Co-Cr, and the mixture was remelted with an oxygen torch. Finally, the material was introduced into the mold utilizing a conventional casting centrifuge.

The precise temperature was measured utilizing an industrial laser thermometer gun. After injection, the mold was set aside for several hours to cool to room temperature. The injected specimens were then removed through sandblasting with aluminum oxide at a pressure of 3 bar, per the manufacturer's directions.

## 2.2. Testing procedures

### 2.2.1. Flexural strength test

The flexural strength was evaluated using a three-point bending test on a Universal Testing apparatus (MC®, China). Before performing the tests, an electronic Fernier caliper was utilized to verify the measurements of every specimen.

### 2.2.2. Testing procedure

The flexural test was done by placing the specimens in a three-point bending universal machine. In order to hold the specimen during testing, 4 extra millimetres of material were added at both sides of specimen. The specimens were held between two supporting arms, the length between them is 34mm for the Cobalt-Chromium, the force was applied by a plunger positioned at the center between these arms. The plunger and the supporting arms were both 2mm in diameter. The force was applied at the center in a direction perpendicular to the longitude of the specimen, resulting in a chisel-like bending between the two supporting pins.

The force was applied gradually at strain rate of 0.1mm/mm/minutes according to manufacturing instruction until fracture of the specimen. According to (ISO 22674:2016) and (ISO 178:2019) the following formula was used to calculate the flexural strength. Formula for flexural strength calculation:

$$T = 3FL/2bd^3 \quad (1)$$

Where, T denotes the transverse strength assessed in megapascals (MPa). F denotes the load at which fracture did happen quantified in newton (N). L denotes the precise distance between two supports (50 mm). The variable "b" represents the measurement of the breadth of the specimens. The value of d represents the thickness of the specimen, which is precisely (2.5 mm).

### 2.2.3. Surface hardness

The surface hardness of the fabricated specimens was assessed according to protocol E92 (ASTM International, West Conshohocken, PA, USA). Vickers microhardness

test was conducted using a tester. Before the test, the device was calibrated according to the manufacturer's instructions. The dwell time was set to 15 seconds, with a micro indentation length and depth of 40 µm and a force of 9.8 N [13]. Each specimen was measured five times, and the mean was used in the analysis per ADA Requirement No. 14.

## 2.3. Statistical analysis

The data were analyzed using GraphPad Prism (version 9.5.0.730; GraphPad Inc., San Diego, CA, USA). Each specimen's compressive strength, surface hardness, and corrosion resistance were assessed and summarized as the mean and standard deviation in each group.

The Shapiro–Wilk test was used to assess the normality of each variable's distribution (Table 1). The data were compared between groups using a one-way analysis of variance (ANOVA) followed by post-hoc pairwise Games–Howell or Bonferroni tests. A  $p < 0.05$  was considered statistically significant.

Table 1. The normality of each variable's distribution.

Variable	Group	Shapiro–Wilk test		
		Statistic	df	p-value
Flexure strength	0%	0.9687	10	0.8786
	6%	0.9325	10	0.4729
	8%	0.8660	10	0.0898
Surface hardness	0%	0.9737	10	0.7069
	6%	0.9532	10	0.7068
	8%	0.9895	10	0.9962

## 3. Results and Discussion

### 3.1. Flexure strength statistics

The experimental group treated with 8% molybdenum disulfide exhibited the highest average value of (0.7094). It was followed by the group treated with 6% molybdenum disulfide, which had an average value of (0.5423) (Figure 3).

The group serving as a control had the smallest mean value of (0.4399), as seen in. A single-way analysis regarding variance (ANOVA) showed a statistically significant difference comparing tested groups at a level of significance (0.0001) (P value < 0.05) as demonstrated in (Table 2).

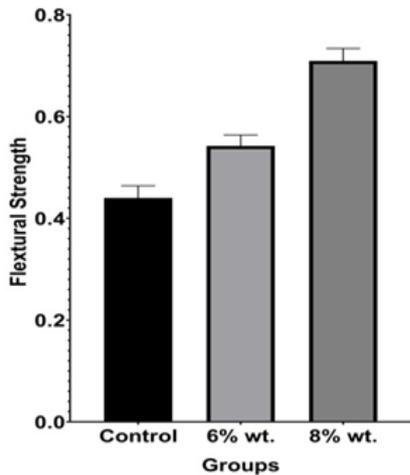
### 3.2. Surface hardness

The mean surface hardness was greatest in the 8%wt MoS<sub>2</sub> group (912.1 IU), followed by the 6%wt MoS<sub>2</sub> group (693.6 IU), and lowest in the 0%wt MoS<sub>2</sub> (control) group (595.3 IU; Figure 4). Surface microhardness values differed significantly among groups ( $p < 0.05$ ; Table 3). In addition, surface microhardness differed significantly between all pairs of groups (Table 4).

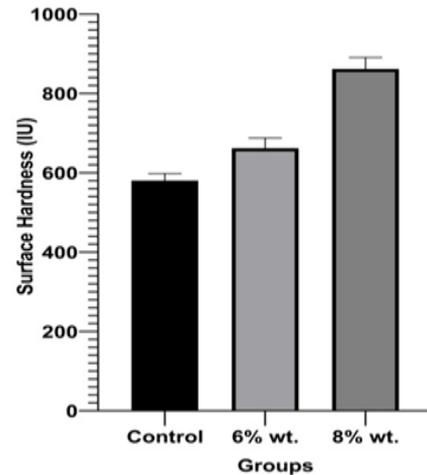
### 3.3. SEM analysis

The characterization of dental biomaterials is crucial to understanding their performance and long-term clinical success. Cobalt-chromium (Co-Cr) alloys have long been used in removable and fixed prosthodontics due to their high mechanical strength, corrosion resistance, and biocompatibility.

Recent studies have explored the incorporation of molybdenum disulfide ( $\text{MoS}_2$ ) into Co-Cr alloys to enhance their tribological and mechanical properties. SEM (Scanning Electron Microscopy) plays a vital role in evaluating the microstructural changes that occur following such modifications (Table 5-7).



**Fig. 3.** Comparison of flexural strength among cobalt-chromium alloy groups with 0%, 6%, and 8% weight additions of molybdenum disulfide ( $\text{MoS}_2$ ).



**Fig. 4.** Surface hardness (IU) of cobalt-chromium alloy groups with 0%, 6%, and 8% weight additions of molybdenum disulfide ( $\text{MoS}_2$ ).

**Table 2.** One-way ANOVA regarding flexure strength testing

ANOVA table	SS	DF	MS	F	P value
Treatment (between columns)	0.3701	2	0.1851	340.4	$P < 0.0001$
Residual (within columns)	0.01468	27	0.0005437		
Total	0.3848	29			

\*Df: the degree of freedom (the variability within and between groups). \*F: the ratio between the average square between groupings and the average square among groupings. and \*P-value: represents the chance of no difference in obtaining a result equal to or higher than what was observed.

Bonferroni's multiple comparisons test	Mean Diff.	Significant?	Summary
Control vs. 6% wt.	-0.1024	Yes	****
Control vs. 8% wt.	-0.2695	Yes	****
6% wt. vs. 8% wt.	-0.1671	Yes	****

**Table 3.** One-way ANOVA of surface microhardness among groups.

Comparison	SS	df	MS	F	p-value
Treatment (between columns)	419409	2	209704	341.2	$< 0.0001$
Residual (within columns)	16594	27	614.6		
Total	436002	29			

**Note:** df, degrees of freedom (variability within and between groups); F, ratio of the average square between and among groups; MS, mean square; SS, sum of squares.

**Table 4.** Pairwise Bonferroni comparisons of surface microhardness among groups.

Comparison	Mean Difference	Significant?	Summary
0% vs. 6% wt.	-81.68	Yes	****
0% vs. 8% wt.	-281.5	Yes	****
6% wt. vs. 8% wt.	-199.8	Yes	****

**Table 5.** Energy Dispersive X-ray Spectroscopy (EDS) Results of control group MO

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	23.9	0.3	6.2	0.1
Si	1.5	0.0	0.9	0.0
Cr	23.5	0.1	26.6	0.1
Fe	0.6	0.0	0.8	0.0
Co	49.1	0.1	62.8	0.1
Mo	1.3	0.1	2.8	0.3

**Table 6.** Energy Dispersive X-ray Spectroscopy (EDS) Results of 6%wt MO group

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	21.0	0.4	5.3	0.1
Si	2.1	0.0	1.2	0.0
Cr	24.8	0.1	27.3	0.1
Co	50.7	0.1	63.2	0.1
Mo	1.4	0.1	2.9	0.2

**Table 7.** Energy Dispersive X-ray Spectroscopy (EDS) Results of 8%wt

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	20.2	0.4	5.1	0.1
Si	1.7	0.0	1.0	0.0
Cr	25.4	0.1	27.6	0.1
Co	50.8	0.1	62.6	0.1
Mo	1.8	0.1	3.7	0.2

The framework of a removable partial denture must possess adequate mechanical qualities to endure the stresses encountered during mastication and speech without deformation or fracture while ensuring support and stability for the denture [14].

Robust mechanical qualities guarantee that the frameworks can endure these stresses while preserving their shape and functionality over time [15]. This study examined the mechanical properties of Co-Cr alloys containing different concentrations of MoS<sub>2</sub> (6%wt and 8%wt by weight). It identified notable differences compared to the control group (0%wt MoS<sub>2</sub>).

### 3.4. Flexure strength

#### 3.4.1. Microstructural refinement and strengthening mechanisms

Molybdenum (Mo) in CoCrMo alloys is known to stabilize the microstructure by forming carbides and reducing grain boundary mobility, which improves mechanical properties such as hardness and wear resistance [1]. While MoS<sub>2</sub> is distinct from elemental Mo, its incorporation could similarly influence the alloy's microstructure (Figure 5). For instance:

- **Grain Boundary Strengthening:** MoS<sub>2</sub> particles may act as grain refiners during solidification, reducing grain size and enhancing resistance to crack propagation under flexural loads.

- **Secondary Phase Formation:** Sulfur from decomposed MoS<sub>2</sub> could form sulfides (e.g., CrS or CoS), which might precipitate at grain boundaries, increasing strength but requiring careful control to avoid brittleness.

#### 3.4.2. Surface hardness

Hardness is a critical property of removable partial denture frameworks, as they must resist deformation caused by functional movements such as chewing. This study used the Vickers hardness test to assess its fabricated specimens.

A flat specimen with a highly polished surface is needed to measure the hardness range of the material [16].

In this study, the hardness scores were higher in the 8%wt and 6%wt MoS<sub>2</sub> groups than in the control group. One study examining Co-Cr-Mo alloys processed through spark plasma sintering indicated that higher sintering temperatures resulted in a finer grain structure and enhanced hardness [17].

The highest average hardness recorded was 797 Vickers, resulting from fine-grain structures and the distribution of oxides within the microstructure. Adding Mo facilitates the development of finer-grain structures in both conventionally cast and additively made alloys, improving mechanical qualities such as compressive strength and hardness [18, 19].

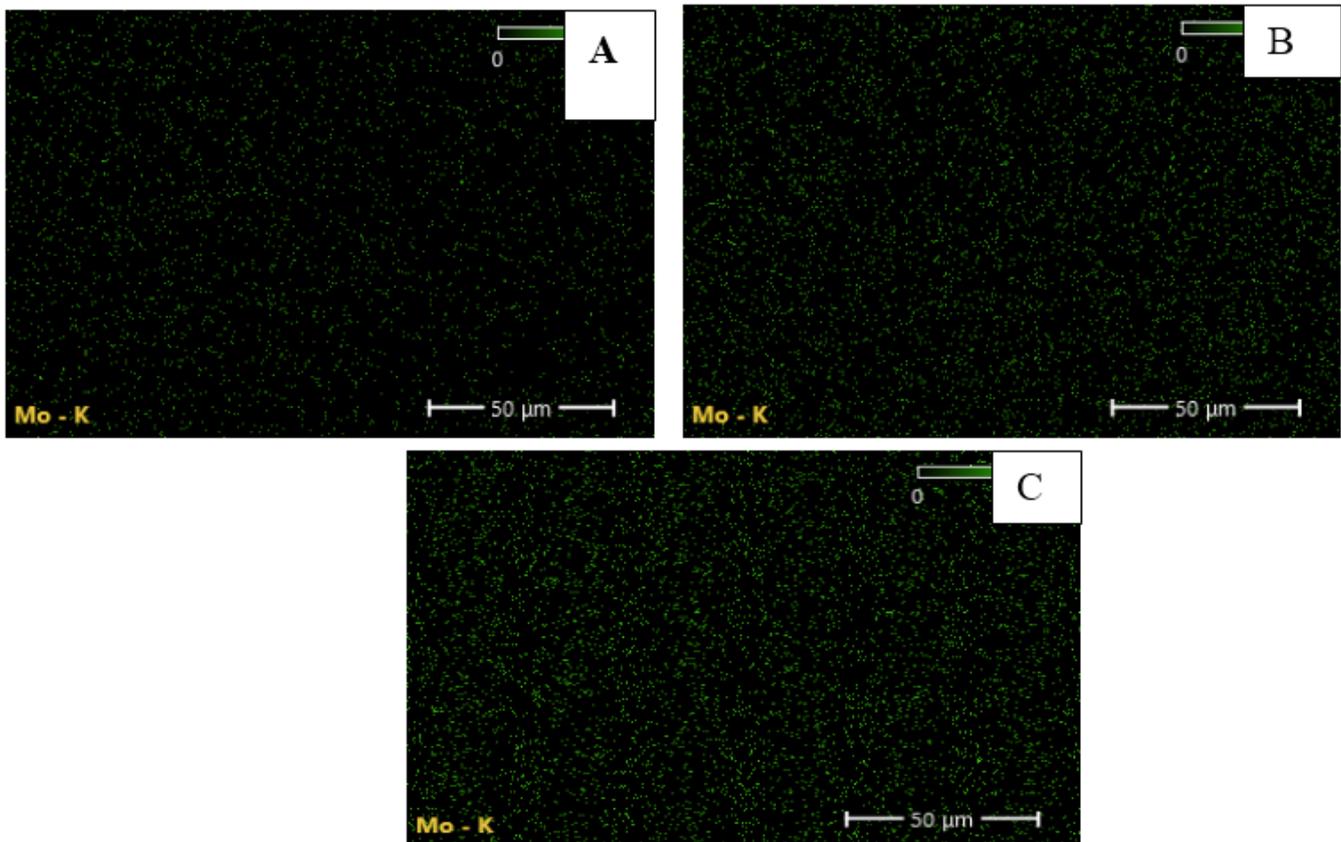


Fig. 5. Distribution of Molybdenum in Co-Cr Alloy Samples A: Control Group. B: 6 wt% Mo. C: 8 wt% Mo

### 3.4.3. Distribution of Molybdenum in Co-Cr alloy samples

#### A: Control Group

The control sample exhibits no detectable molybdenum (Mo) presence, as expected. The SEM-EDS mapping shows a uniform distribution of cobalt (Co) and chromium (Cr), indicating a homogeneous Co-Cr matrix without Mo incorporation.

#### B: 6 wt% Mo

In the 6 wt% Mo sample, SEM-EDS mapping reveals discrete regions of Mo enrichment. These localized areas suggest the formation of Mo-rich phases or precipitates within the Co-Cr matrix. The presence of such phases can enhance the alloy's mechanical properties, including hardness and wear resistance, due to solid solution strengthening and the formation of hard intermetallic compounds.

#### C: 8 wt% Mo

The 8 wt% Mo sample displays a more uniform and intense Mo distribution across the alloy matrix. This homogeneity indicates improved Mo solubility and integration within the Co-Cr lattice at higher concentrations. Such uniform distribution is associated with enhanced mechanical properties and corrosion resistance, as Mo contributes to the formation of stable passive films on the alloy surface.

The progression from the control to the 8 wt% Mo

sample demonstrates the impact of increasing Mo content on the microstructural characteristics of Co-Cr alloys. The enhanced and more uniform distribution of Mo at higher concentrations correlates with improved mechanical properties and corrosion resistance, making these alloys suitable for biomedical applications such as dental prosthetics and orthopedic implants.

## 4. Conclusion

Dental prostheses play a critical role in restorative dentistry, significantly contributing not only to the improvement of oral functionality but also to enhancing aesthetics and overall oral health. Among the various materials employed for the construction of dental frameworks, cobalt-chromium (Co-Cr) alloys are widely favored due to their exceptional corrosion resistance and high mechanical strength, which make them durable and reliable for long-term use. In a recent study, researchers investigated the effects of incorporating molybdenum disulfide ( $\text{MoS}_2$ ) into Co-Cr alloys at varying concentrations—specifically 0%wt, 6%wt, and 8%wt—on the mechanical properties and corrosion resistance of these dental materials. A total of 90 specimens were fabricated, with 30 samples assigned to each concentration group, to evaluate their compressive strength, hardness, and resistance to corrosion under controlled conditions. The results of the study demonstrated that the addition of  $\text{MoS}_2$  significantly

enhanced the mechanical characteristics of the Co-Cr alloy. Notably, compressive strength and hardness values varied significantly among the groups, with statistical analysis confirming differences at a significance level of  $p < 0.05$ . The group with the highest concentration of MoS<sub>2</sub> (8%wt) exhibited the greatest improvements, achieving a compressive strength of 141.3 MPa and a hardness value of 912.1 IU. These values were followed by those in the 6%wt MoS<sub>2</sub> group, which recorded a compressive strength of 131 MPa and a hardness value of 693.6 IU. In contrast, the group with no MoS<sub>2</sub> incorporation (0%wt) displayed the lowest performance metrics, with a compressive strength of 87.72 MPa and a hardness value of 595.3 IU. These findings suggest that increasing the concentration of MoS<sub>2</sub> in Co-Cr alloys directly correlates with enhanced mechanical properties, making the material more robust and better suited for demanding dental applications. In addition to mechanical improvements, the study also revealed that corrosion resistance was markedly enhanced with higher concentrations of MoS<sub>2</sub>. The 8%wt MoS<sub>2</sub> group exhibited the greatest resistance to corrosion, attributed to the role of molybdenum (Mo) in facilitating the formation of a protective oxide layer on the alloy's surface. This oxide layer acts as a barrier against corrosive agents, thereby extending the material's longevity and maintaining its structural integrity over time. Such improvements are particularly advantageous for dental prostheses, which are constantly exposed to challenging conditions in the oral environment, including variations in pH levels, moisture, and microbial activity.

The findings from this study underscore the potential benefits of incorporating MoS<sub>2</sub> into Co-Cr dental alloys to create prostheses that are not only stronger but also more durable and resistant to degradation. These advancements could lead to longer-lasting dental restorations that reduce the need for frequent replacements or repairs, ultimately benefiting both dental practitioners and patients by improving treatment outcomes and reducing costs over time. However, while these initial results are promising, further research is necessary to fully understand the long-term clinical performance and biocompatibility of MoS<sub>2</sub>-enhanced Co-Cr alloys. Future studies should focus on evaluating their behavior under real-world conditions within the oral cavity, as well as assessing any potential biological interactions to ensure safety and effectiveness for widespread use in dental applications.

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