

Effect of a Metal-Ceramic Bonding Agent on the Bond Strength of Selective Laser Melted Cobalt-Chromium Alloy to Two Different Veneering Porcelains: An In Vitro Study

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ABSTRACT

Background: The integrity of the metal-ceramic interface is critical to the performance of porcelain-fused-to-metal restorations. The use of a bonding agent may improve the interaction between additively manufactured cobalt-chromium alloy and veneering porcelain.

Aim: To evaluate the effect of a metal-ceramic bonding agent on the bond strength between selective laser melted (SLM) cobalt-chromium (Co-Cr) alloy and two commercially available veneering porcelains.

Materials and Methods: Forty standardized SLM Co-Cr specimens were divided into four groups (n=10): IPS InLine without bonding agent, IPS InLine with bonding agent, Vintage Halo without bonding agent, and Vintage Halo with bonding agent. Specimens underwent standardized surface preparation and veneering procedures and were tested using a three-point flexural bond test according to ISO 9693. Failure modes were examined stereomicroscopically. Data were analyzed using one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference test; $p < 0.05$ was considered statistically significant.

Results: Mean bond strength was 35.52 ± 1.05 MPa for IPS InLine without bonding agent and 41.62 ± 0.88 MPa with bonding agent. For Vintage Halo, mean bond strength was 31.15 ± 0.82 MPa without bonding agent and 38.22 ± 0.69 MPa with bonding agent. All groups exceeded 25 MPa. ANOVA demonstrated a significant difference among groups ($F=248.50$, $p < 0.001$), and all pairwise Tukey comparisons were significant ($p < 0.001$). Untreated specimens predominantly showed adhesive failure, whereas bonding-agent groups showed mixed and cohesive failure patterns.

Conclusion: Within the limitations of this in vitro study, the bonding agent significantly increased bond strength for both veneering porcelains. IPS InLine showed higher bond strength than Vintage Halo in both bonding conditions.

Keywords: selective laser melting; cobalt-chromium; metal-ceramic bond; bonding agent; veneering porcelain; IPS InLine; Vintage Halo.

I. INTRODUCTION

Metal-ceramic restorations remain an important treatment option in fixed prosthodontics because they combine the rigidity and impact resistance of a metallic substructure with the aesthetic and functional properties of veneering ceramic. Despite increasing use of all-ceramic systems, porcelain-fused-to-metal restorations continue to be used when strength and predictable clinical performance are required.

The long-term success of a metal-ceramic restoration depends not only on the properties of the individual materials but also on the integrity of the metal-ceramic interface. Bonding is influenced by mechanical interlocking, physical forces, and chemical interaction between the metal oxide layer and ceramic. Surface preparation and control of oxide formation therefore have a major influence on the final bond.

Cobalt-chromium alloys are widely used because of their mechanical strength, corrosion resistance, biocompatibility, and cost efficiency. The development of CAD/CAM and additive manufacturing has expanded their use. Selective laser melting produces metal frameworks through layer-by-layer fusion of alloy powder and can reduce some variables associated with conventional casting.

Bonding of porcelain to SLM Co-Cr depends on surface condition, oxide formation, thermal compatibility, and ceramic composition. Airborne-particle abrasion increases surface roughness and promotes micromechanical retention, while the oxide layer contributes to chemical bonding. Metal-ceramic bonding agents have been proposed as intermediate layers that may improve surface wetting and chemical interaction between metal and ceramic.

Because the effect of a bonding agent may depend on the alloy, manufacturing process, and veneering ceramic, its performance should be evaluated for specific material combinations. The present study therefore evaluated the effect of a universal metal-ceramic bonding agent on the bond strength between SLM Co-Cr alloy and two commercially available veneering porcelains, IPS InLine and Vintage Halo, and assessed the resulting failure modes.

II. AIM AND OBJECTIVES

Aim: To comparatively evaluate the effect of a bonding agent on the bond strength between SLM Co-Cr alloy and two commercially available veneering porcelains.

Primary objective: To evaluate the effect of a bonding agent on the bond strength between SLM Co-Cr alloy and the two veneering porcelains.

Secondary objectives: (1) To compare the effect of the bonding agent between the two veneering porcelains; and (2) to evaluate the type of bond failure after bond-strength testing.

III. MATERIALS AND METHODS

Study design and sample size. This experimental in vitro study included 40 specimens, with 10 specimens allocated to each of four groups. The sample size was estimated using OpenEpi 2.3 with an effect size of 0.25, 80% power, 5% alpha error, and a 95% confidence interval.

Materials. EOS CobaltChrome EP1 Co-Cr alloy powder (EOS GmbH, Munich, Germany), IPS InLine (Ivoclar Vivadent AG, Schaan, Liechtenstein), Vintage Halo (Shofu Dental GmbH, Ratingen, Germany), Dentsply Sirona Universal Bonder, and 110 μ m aluminum oxide abrasive were used. SLM fabrication was performed using an EOSINT M270 system. Ceramic firing was performed using a Vita Vacumat 40 furnace. Mechanical testing was performed using a Krystal Elmec Universal Testing Machine with a three-point bending jig, and failure surfaces were examined using a Magnus MS13 stereomicroscope.

Specimen fabrication and surface preparation. Standardized rectangular metal beams measuring 25 mm $\times$ 3 mm $\times$ 0.5 mm were digitally designed and fabricated using SLM. The bonding surface was airborne-particle abraded using 110 μ m aluminum oxide. Specimens were then cleaned and allocated to the experimental groups.

Experimental groups. Group A1 comprised SLM Co-Cr with IPS InLine without bonding agent; Group A2 comprised SLM Co-Cr with IPS InLine with bonding agent; Group B1 comprised SLM Co-Cr with Vintage Halo without bonding agent; and Group B2 comprised SLM Co-Cr with Vintage Halo with bonding agent.

Porcelain application. In the experimental groups, the bonding agent was applied as a thin, uniform layer to the prepared Co-Cr surface and fired according to the specified protocol. Opaque, dentin, and enamel porcelain layers were subsequently applied. A standardized split mold was used to obtain a final ceramic veneer dimension of approximately 8 mm $\times$ 3 mm $\times$ 1.1 mm. Specimens underwent the prescribed firing and glazing cycles.

Bond-strength testing. Metal-ceramic bond strength was evaluated using a standardized three-point flexural test in accordance with ISO 9693. Each specimen was positioned symmetrically on the testing jig and loaded at a controlled crosshead speed until fracture or interfacial debonding. The maximum failure load was recorded and bond strength was expressed in MPa.

Failure-mode analysis. Fractured interfaces were examined using a stereomicroscope. Failure was categorized as adhesive when separation occurred primarily at the metal-ceramic interface, cohesive when fracture occurred within the ceramic, or mixed when both patterns were present.

Statistical analysis. Descriptive statistics were calculated for each group. One-way ANOVA was used to compare the four groups, followed by Tukey's HSD test for pairwise comparisons. Statistical significance was set at $p < 0.05$.

IV. RESULTS

Forty specimens were fabricated and tested. All four groups demonstrated mean bond-strength values above the 25 MPa minimum requirement stated in ISO 9693. The highest mean bond strength was observed in Group A2, followed by B2, A1, and B1.

Table 1. Distribution of study groups

Group	Alloy	Veneering porcelain	Bonding agent
A1	SLM Co-Cr	IPS InLine	Absent
A2	SLM Co-Cr	IPS InLine	Present
B1	SLM Co-Cr	Vintage Halo	Absent
B2	SLM Co-Cr	Vintage Halo	Present

Table 2. Descriptive statistics of metal-ceramic bond strength

Group	n	Mean (MPa)	SD	Minimum	Maximum
A1 – IPS InLine control	10	35.52	1.05	33.55	37.05
A2 – IPS InLine + bonding agent	10	41.62	0.88	40.5	43.2
B1 – Vintage Halo control	10	31.15	0.82	30.05	32.5
B2 – Vintage Halo + bonding agent	10	38.22	0.69	37.2	39.25

One-way ANOVA demonstrated a statistically significant difference among the four groups ($F=248.50$, $p<0.001$). Tukey's HSD test showed significant differences for every pairwise comparison ($p<0.001$). The bonding agent increased mean bond strength by 6.10 MPa for IPS InLine and by 7.07 MPa for Vintage Halo. IPS InLine also showed higher mean bond strength than Vintage Halo under both bonding conditions.

Table 3. One-way ANOVA and Tukey's HSD results

Comparison	Mean difference / statistic	p-value
Overall ANOVA	$F=248.50$	<0.001
A1 vs A2	-6.10	<0.001
A1 vs B1	4.37	<0.001
A1 vs B2	-2.70	<0.001
A2 vs B1	10.47	<0.001
A2 vs B2	3.40	<0.001
B1 vs B2	-7.07	<0.001

Microscopic examination showed predominantly adhesive failures in the untreated control groups. Specimens treated with bonding agent demonstrated a shift toward mixed and cohesive failure patterns.

V. DISCUSSION

The principal finding of this study was that application of the bonding agent significantly increased bond strength for both veneering porcelain systems. Mean bond strength increased from 35.52 ± 1.05 MPa to 41.62 ± 0.88 MPa for IPS InLine and from 31.15 ± 0.82 MPa to 38.22 ± 0.69 MPa for Vintage Halo.

All untreated groups exceeded the ISO 9693 threshold, indicating that the SLM Co-Cr substrate provided an adequate baseline bond under the conditions tested. The additional increase produced by the bonding agent suggests that the intermediate layer may have enhanced interaction at the metal-ceramic interface.

IPS InLine demonstrated higher absolute bond strength than Vintage Halo both without and with bonding agent. Thus, the bonding agent did not eliminate differences between the ceramic systems. Differences in ceramic composition and thermomechanical behavior may contribute to this finding.

The failure-mode observations supported the quantitative results. Untreated specimens predominantly exhibited adhesive failure, whereas bonding-agent groups demonstrated mixed and cohesive patterns. The shift away from predominantly adhesive failure suggests improved interfacial integrity under the test conditions.

The study has limitations. It was conducted in vitro under controlled static loading and therefore does not reproduce the complex oral environment. Thermocycling, moisture, cyclic loading, pH fluctuations, and long-term fatigue may influence the metal-ceramic interface. Only two veneering porcelains and one bonding agent were evaluated; therefore, the findings should not be generalized to other materials or manufacturing systems.

Further studies incorporating thermocycling, dynamic fatigue, additional ceramic systems, and alternative bonding agents are warranted. Surface and interfacial characterization may also help clarify the mechanisms responsible for the observed improvement.

VI. CONCLUSION

The universal metal-ceramic bonding agent significantly increased the bond strength between SLM Co-Cr and both IPS InLine and Vintage Halo under the conditions of this in vitro study.

IPS InLine demonstrated higher mean bond strength than Vintage Halo in both bonding conditions.

All four study groups exceeded the 25 MPa ISO 9693 threshold.

The bonding-agent groups showed a shift from predominantly adhesive failure toward mixed and cohesive failure.

Within the limitations of this study, use of a compatible bonding agent may improve the predictability of porcelain bonding to SLM Co-Cr frameworks.

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