

Effect of surface treatment of milled cobalt–chromium alloy on shear bond strength to porcelain

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Background/aim

Strong bond between metal and porcelain is essential for success and longevity of porcelain-fused-to-metal restorations. Therefore, the present study aimed to evaluate shear bond strength (SBS) between porcelain and CAD/CAM milled cobalt–chromium (Co–Cr) alloy treated by sandblasting, oxidation, and laser etching in comparison with cast alloy treatment.

Materials and methods

Co–Cr alloys were used for fabrication of sixty discs (2.5 mm thickness×10 mm diameters), which were split into half ($n=30$ each): group A, milled discs, and group B, conventional casting discs. Both groups were split into thirds ($n=10$) according to Co–Cr surface treatment: subgroup S, sandblasting (control); subgroup O, oxidation; and subgroup L, laser etching. Surface morphology of the samples was examined before and after surface treatments by scanning electron microscope. Feldspathic porcelain (3 mm thickness×5 mm diameter) was added to the Co–Cr discs (opaque, dentin, and enamel) and fired. SBS test (MPa) was carried out using material testing machine at crosshead speed of 0.5 mm/min till failure. The modes of failure were evaluated by scanning electron microscope and digital microscope. Statistics were performed by two-way analysis of variance (ANOVA), one-way ANOVA, Tukey post-hoc test, and t -test ($P<0.05$).

Results

Two-way ANOVA results indicated insignificant differences in SBS among Co–Cr fabrication techniques ($P=0.259$). In contrast, significant differences were demonstrated between the different surface treatments ($P<0.001$), where laser etching showed the least SBS mean values with both fabrication techniques. Regardless of the fabrication technique, all subgroups exhibited cohesive failure within the porcelain, except for the laser etching subgroups, which showed mixed failure mode.

Conclusion

Bond between surface treated Co–Cr alloys and porcelain is independent of the fabrication technique. Laser etching recorded the least SBS among the tested surface treatments irrespective of the fabrication technique. All SBS values recorded in the present study were clinically acceptable.

Keywords:

casting, cobalt–chromium alloys, laser etching, milling, oxidation, sandblasting, shear bond strength

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Introduction

In spite of the rapid advancements in the development of newer and stronger ceramic systems [1], porcelain-fused-to-metal restorations remains the ‘gold standard’ in prosthetic dentistry [2]. They combine the biomechanical advantages of metals with the excellent esthetics of ceramic materials [3]. Base-metal alloys are often used for fabrication of the metallic substrate of porcelain-fused-to-metal restorations. Unfortunately, Ni–Cr alloys may cause allergic reactions; therefore, cobalt–chromium (Co–Cr) alloys are the best substitute for allergic patients [4]. Co–Cr alloys are increasingly used because of their lower cost in comparison with noble alloys, biocompatibility, elevated strength, and

modulus of elasticity, as well as corrosion resistance. On the contrary, their high melting range makes their manipulation difficult by the lost-wax casting technique. Moreover, they suffer from difficulties in finishing and polishing owing to their increased hardness and decreased ductility [4,5].

Lost-wax casting technique was traditionally used for fabrication of Co–Cr restorations. The many steps in this technique increase the number of variables that can

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cause discrepancies in the final restoration [4,5]. CAD/CAM technologies have revolutionized Co–Cr restoration production by either subtractive or additive techniques [6–10]. CAD/CAM hard milling is one of the subtractive methods for construction of Co–Cr restorations in which defects and porosities (occurred during casting) are decreased by the use of the industrially prefabricated Co–Cr alloy block. However, increased rigidity of the block leads to increased tool and machine wear, thereby increasing the maintenance costs, which was considered the principal drawback of this technique. Selective laser melting is one of the additive construction techniques of Co–Cr prosthesis, where fine layers of metal powder are fused together by the aid of laser beam. Unfortunately, this technique is highly expensive. Another technique for fabrication is the CAD/CAM soft milling of Co–Cr block; it is called soft because the block consisted of alloy powder that is finely dispensed in a binder material that can be burned out. After milling, the restoration is sintered in a special sintering furnace using argon gas. The chief advantage of this technique is the decreased milling time and cost over hard milling [6–10].

Bonding between porcelain and metal is a crucial factor for success and longevity of porcelain-fused-to-metal prosthesis. Many authors [8–11] tested the bond between porcelain and Co–Cr alloys constructed by contemporary methods compared with cast one and declared that alloys constructed by these methods could be an encouraging substitute for porcelain-fused-to-metal prosthesis.

Wang *et al.* [8] and Mhaske *et al.* [9] reported that Co–Cr alloy fabrication technique greatly affected the bond strength between ceramic and alloy with superiority of alloys fabricated by the contemporary techniques over those fabricated by conventional casting.

Other authors found that Co–Cr alloy fabrication technique had no effect on bond with porcelain. Co–Cr alloys fabricated with contemporary techniques exhibited equivalent bond with ceramic to that of castable alloy [12–15]. Juntavee and Oeng [11] revealed that CAD/CAM sintered metal alloy is favored for porcelain-fused-to-metal restoration, as it had a reliable shear bond strength (SBS) compared with cast alloys. Similarly, Stawarczyk *et al.* [12] reported that porcelain bond strength to CAD/CAM base metal alloys was close to that of conventional cast alloys. Additionally, Serra-Prat *et al.* [13] showed that cast, milled, and laser sintered Co–Cr alloys recorded insignificant bond strength differences with porcelain.

They declared that porcelain adhesion values for all the tested alloys were adequate for clinical applications [13]. Similar findings were reported by Dimitriadis *et al.* [14].

The foremost demand for victorious porcelain-fused-to-metal restoration is the everlasting bond between its two components. Chipping or fracture of porcelain is a grave problem that causes functional and esthetic inconveniences. Several surface treatments were carried out in the literature to enhance the bond between base metal alloys and porcelain, through increasing the wettability of the metal by porcelain and controlling the thickness of the oxide layer. Among these treatments are sandblasting, oxidation heat treatment, acid etching, laser etching, application of bonding agents, mechanical roughness with carbide burs or diamond tips, and combination between the different surface treatments [16–19].

Controversial results are present in the literature regarding the best universal surface treatment that improves the bond between base metals and ceramics. Lombardo *et al.* [16] reported that Al₂O₃ sandblasting enhanced SBS of Co–Cr alloy to porcelain than those roughened with tungsten bur [16]. Another study supported the superiority of sandblasting surface treatment over Nd:YAG laser etching in improving the SBS between the treated metal and porcelain [17]. On the contrary, the results of Deepak *et al.* [18] manifested that Nd:YAG laser-etched Co–Cr alloy had higher SBS with porcelain than those treated by sandblasting, oxidation, heat treatment, degassing, and outgassing. The aim of oxidation surface treatment of alloy is the removal of entrapped gas as well as surface contaminants and the formation of oxide layer [20–22]. Some authors demonstrated that oxidation did not affect base metal-porcelain bond [19,23]. Others declared that degassing the alloy before porcelain application increased the bond between metal and porcelain [24–26].

Scarce articles are present in the recent literature regarding the effect of different surface treatments of milled Co–Cr alloys on bond strength to porcelain. Hence, the aim of this research was to evaluate SBS between porcelain and milled Co–Cr alloy treated by sandblasting, oxidation, and laser etching in comparison with cast alloy treatment.

The first null hypothesis was that alloy fabrication technique had no effect on SBS between porcelain and milled as well as cast Co–Cr alloys. The second null hypothesis was that Co–Cr surface treatments would not affect SBS.

Materials and methods

Materials

- (1) Co–Cr blank (Copra Sintec K, 98×16 mm/chemical composition: Co balance, Cr 26.5–30%, Mo 4.5–7%, Mn 0–1%, Si 0–1%, Fe 0–1%, C 0–0.35, other <1%; White Peaks Dental Solutions GmbH & Co. KG, Hamminkeln, Germany).
- (2) Co–Cr alloy (Kera C, chemical composition: Co 60%, Cr 24.5%, W 9%, Nb 2%, V 2%, Mo 1.1%, Fe 0.15%, Si 0.9%, others <0.1; Eisenbacher Dentalwaren ED GmbH, Woerth/Main, Germany).
- (3) Machinable wax blank (Copra wax, 98×16 mm, White Peaks Dental Solutions GmbH & Co. KG).
- (4) Feldspathic porcelain (VITA VMK Master, Vita Zahnfabrik, Germany).

Study design

Co–Cr alloys were used for fabrication of sixty discs (2.5 mm thickness×10 mm diameters) which were divided into two groups ($n=30$ each): group A, milled discs, and group B, conventional casting discs. Both groups were split into three subgroups ($n=10$) according to Co–Cr surface treatment: subgroup S, sandblasting (control); subgroup O, oxidation; and subgroup L, laser etching. Feldspathic porcelain (3 mm thickness×5 mm diameter) was added and fired into the Co–Cr discs. SBS test (MPa) was carried out utilizing material testing machine.

Ethical consideration

According to the Ethical Committee of the National Research Centre, this in-vitro study requires no ethical consideration following Helsinki Declaration.

Methods

Fabrication of the cobalt–chromium discs

Fabrication by CAD/CAM soft milling technique

Standardized 30 discs were fabricated by the CAD/CAM soft milling/postsintering technique according to the following steps:

- (1) Designing of the discs: design of Co–Cr discs (2.5 mm thickness×10.0 mm diameter) was performed by the use of an open-source 3D computer graphics software (Blender 2.78, Amsterdam, the Netherlands). The disc shape was designed in the form of 2D model, which is 8.5% larger than the desired final size to compensate for sintering shrinkage of the alloy that occurred during the sintering stage.
- (2) Milling of the discs: a Co–Cr blank specific for the soft milling procedure (Copra Sintec K, 98×16 mm; White Peaks Dental Solutions GmbH & Co. KG) was used in this study. The inLab 15 CAM software was used for the milling procedure, which was carried out in the inLab MC X5 milling machine following the dry milling protocol (Sirona Dental Systems GmbH, Bensheim, Germany).
- (3) Sintering of the discs: after milling, the samples were sintered in a high-temperature sintering furnace (in Fire HTC speed; Sirona Dental Systems GmbH, Bensheim, Germany) under Argon protective atmosphere for 5 h at 1280°C with 1 h holding time at the sintering temperature using the special sintering tray and its cover as well as sintering bell as recommended by the manufacturer.

Fabrication by lost-wax casting technique

A total of 30 discs were fabricated by conventional casting technique. To standardize their shape and dimensions, all wax patterns were fabricated by the CAD/CAM technology. The wax patterns were designed similar to the CAD/CAM fabricated discs but without the 8.5% size enlargement. Using the inLab 15 CAM software, wax patterns were milled from a wax blank (Copra wax, 98×16 mm; White Peaks Dental Solutions GmbH & Co. KG) using inLab MC X5 milling machine.

Milled wax patterns were sprued (hinrivest KB; Ernst Hinrichs Dental, Goslar, Germany), and surfactant (Aurofilm, Bego, Germany) was added. The ring was then invested (160 g powder/29 ml liquid; Bellavest SH & Begosal Mixing Liquid, Bego, Germany). Burn-out was carried in an oven (Midtherm 200 MP; Bego, Germany), and then Co–Cr alloy (Kera C; Eisenbacher Dentalwaren ED GmbH) was cast in an induction casting machine (Fornax 35 HF induction casting machine, 10060 S; Fornax, Secondo di Pinerolo, Italy) at the manufacturer-recommended casting temperature (1485°C). The investment was removed by airborne particle abrasion with 250 µg aluminum oxide (Al_2O_3) in a sandblaster (Duoster F1, Bego) at 5–7 bar pressure, and sprues were cut by carbide disks at low speed. Co–Cr discs were ultrasonically cleaned (Sonic Clean; Transkit System, Thebarton, South Australia) in distilled water for 5 min and dried by oil free air spray. All discs were checked for any defect or incompleteness using magnification loupes with a power of 2.5x (Task Vision, New Jersey, USA).

Surface topography of a representative samples from CAD/CAM soft milled and cast groups was evaluated by scanning electron microscope (SEM) (Quanta FEG 250 Environmental Scanning Electron Microscope, Amsterdam, the Netherlands) operating at 200 V–30 kV.

Surface treatments of the cobalt–chromium discs

Sandblasting (control)

In group S, the Co–Cr discs were subjected to sandblasting with 110 µg Al₂O₃ for the milled and the cast discs (following the manufacturer recommendations) at 2 bar pressure, for 10 s, and 10 mm distance between the nozzle and the disc surface (Micro-Blaster; Yantai, Shandong, China) using a specially fabricated holder [11].

Oxidation

In group O, the milled and cast samples were first subjected to oxidation cycle. which was performed in the ceramic furnace (Programat P310 furnace; Ivoclar Vivadent, Schaan, Liechtenstein) at 980°C (heating rate: 80°C/min) for 5 min under vacuum as recommended by the manufacturer. Second, the same samples were sandblasted with 110 µg Al₂O₃ particles following the same protocol performed with the sandblasting subgroups to remove the present oxide layer thoroughly following the manufacturer recommendations.

Laser etching

In sgroup L, the laser surface treatment was achieved using Nd : YAG laser with a wavelength of 1064 nm, energy level of 120 mJ, frequency level of 10 Hz, and a power setting of 6 kW (Neolaser L; Girrbach Dental Systems, Pforzheim, Germany). The samples were irradiated by means of a glass fiber of the Nd : YAG with linear movements perpendicular to the surface of the sample [17].

After different surface treatments, ultrasonic cleaner with distilled water was used to clean the samples for 5 min and then oil-free air spray was used for their dryness. Finally, surface morphology of representative sample from each subgroup was observed by SEM.

Porcelain veneering of the cobalt–chromium discs

To standardize the thickness and shape of the veneering porcelain for all samples, a specially designed split teflon mold was fabricated for addition of porcelain in the form of disc (3 mm thickness×5 mm diameter) on the treated metal disc.

Porcelain build-up procedure was carried out by the layering technique using feldspathic porcelain (VITA VMK Master, Vita Zahnfabrik, Germany) that fired in the porcelain furnace.

Opaque porcelain was first applied to the treated Co–Cr discs, and the opaque layers were done in two stages: wash bake (960°C) and opaque firing (950°C). This was followed by dentin and enamel porcelain application and firing (930°C) then autoglaze firing (920°C). Porcelain was applied, condensed, and fired according to the manufacturer's recommendations.

Shear bond strength testing

Each sample was mounted on a computer-controlled material testing machine (Model 3345; Instron Industrial Products, Norwood, MA, USA) with a load cell of 5 kN. Data were registered using computer software (Bluehill Lite; Instron Instruments, Norwood, Massachusetts, USA). Discs were attached to the lower compartment of testing machine by tightening screws through metallic custom-made housing device with central cavity (10×2.5 mm) into which the disc fitted. Compressive load was applied at metal-porcelain interface using a mono-beveled chisel-shaped metallic rod attached to the upper movable compartment of testing machine traveling at cross-head speed of 0.5 mm/min (Fig. 1). The debonding load was recorded in Newton.

To calculate SBS, load at failure was divided by interfacial bonding area to express the bond strength in MPa using the following equation: $\tau = P/\pi r^2$, where τ =SBS (MPa), P =load at failure (N), π =3.14, and r =radius of the porcelain disc.

Failure mode analysis

The de-bonding surfaces were examined under digital microscope (Scope Capture Digital Microscope, Guangdong, China) and SEM for characterizing the failure modes, which were classified into cohesive failure in metal, adhesive failure at metal-porcelain junction, cohesive failure in porcelain, and mixed type of failure [11].

Statistical analysis

The mean and SD values were calculated for each group in each test. Data were explored for normality using Kolmogorov–Smirnov and Shapiro–Wilk tests, and data showed parametric (normal) distribution. The two-way analysis of variance (ANOVA) was used to test the interaction between different variables

(fabrication technique and surface treatment). Independent sample *t*-test was used to compare between two groups in non-related samples. One-way ANOVA followed by Tukey post-hoc test was used to compare between more than two groups in nonrelated samples. The significance level was set at *P* less than or equal to 0.05 for all tests. Statistical analysis was performed with IBM SPSS Statistics (New York, USA) Version 20 for Windows.

Results

Shear bond strength results

Effect of fabrication techniques on shear bond strength:

With all tested surface treatments, two-way ANOVA results indicated insignificant differences between

CAD/CAM milled (group A) and conventionally cast (group B) Co–Cr samples ($P=0.259$). Conventionally cast group recorded higher SBS mean values than CAD/CAM Milled group ($P<0.001$). The interaction between the two variables had insignificant influence, with *P* value of 0.940 (Table 1).

Effect of surface treatment on shear bond strength

With both fabrication techniques, significant differences were found between sandblasting, oxidation, and laser-etching subgroups ($P<0.001$). With both fabrication techniques, significant differences were found between laser etching subgroup and each of sandblasting and oxidation subgroups. On the contrary, insignificant difference was found between sandblasting and oxidation subgroups. With both fabrication techniques, the highest SBS mean value was recorded in sandblasting subgroup followed by oxidation subgroup, whereas the least mean value was recorded with laser-etching subgroup (Table 1).

Scanning electron microscope results

Cobalt–chromium discs before surface treatment

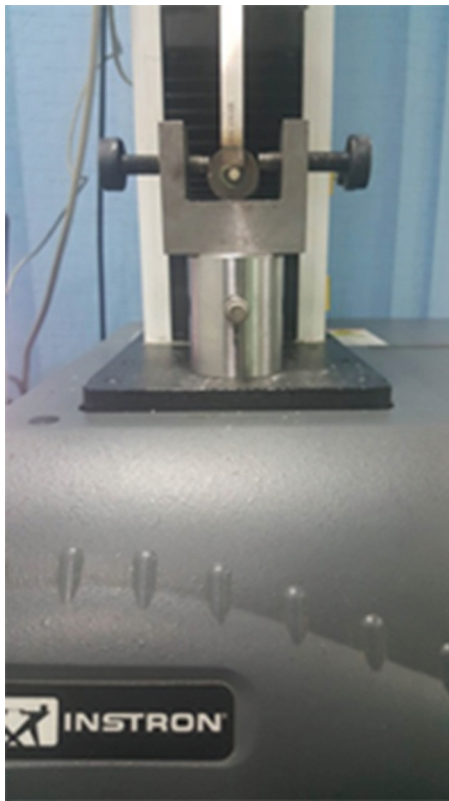
Surfaces of untreated samples were different in morphological appearance. SEM analysis pictures of the cast Co–Cr disc exhibited noticeable dendritic microstructure with interdendritic regions with minimal porosity that is typical of cast alloy [27,28]. Conversely, the microstructure of the CAD/CAM milled Co–Cr disc showed a large grain size with homogenous and completely isolated microporosity, which is typical for free sintering process [27,28] (Fig. 2a and b).

Cobalt–chromium discs after surface treatments

Observation of surface topographic appearance of metal discs after different surface treatments revealed the followings:

- (1) Sandblasting: sandblasted cast Co–Cr sample exhibited a dendritic pattern that resemble the

Figure 1



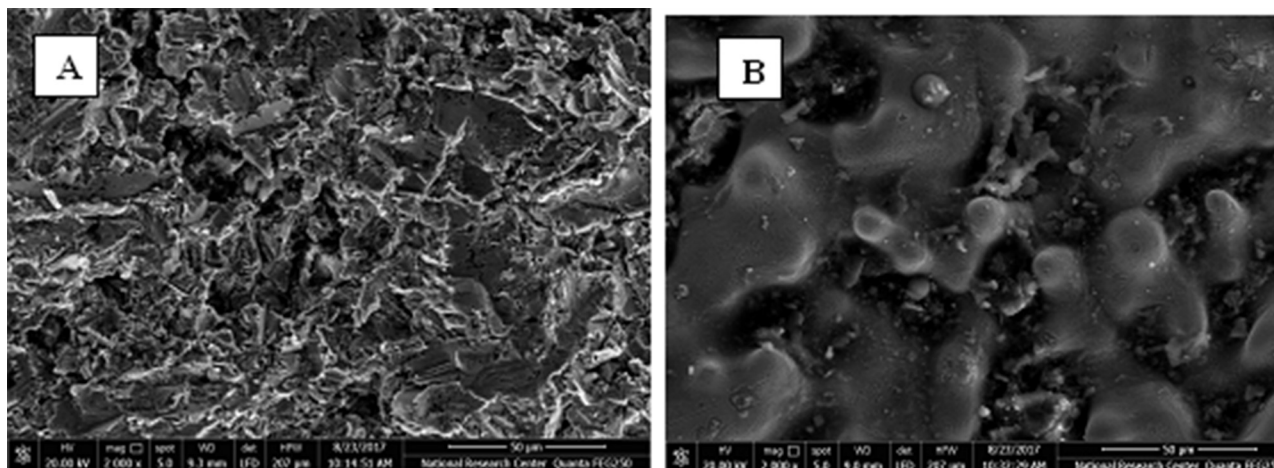
Shear bond strength testing.

Table 1 Mean, SD, and descriptive statistics of shear bond strength in different groups

Variables	Group A: CAD/CAM milled		Group B: conventional casting		<i>P</i> value
	Mean	SD	Mean	SD	
Group S: sandblasting	45.65 ^{a,A}	5.32	48.16 ^{a,A}	6.15	0.511 (NS)
Group O: oxidation	40.65 ^{a,A}	4.33	43.30 ^{a,A}	5.22	0.409 (NS)
Group L: laser etching	26.88 ^{b,A}	4.40	28.08 ^{b,A}	4.41	0.677 (NS)
<i>P</i> value	<0.001		<0.001		

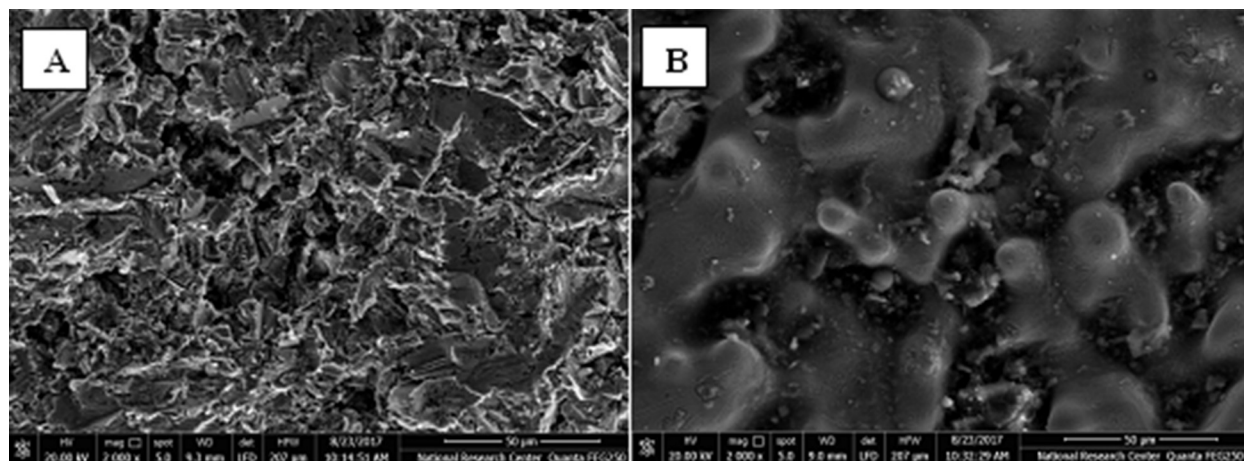
Means with different small letters in the same column indicate significant difference, using two-way analysis of variance at $P<0.05$. Means with A capital letter in the same row indicate insignificant difference (NS), using two-way analysis of variance at $P>0.05$.

Figure 2



Scanning electron microscope figure of Co–Cr alloy at 2000x before surface treatment fabricated by conventional casting (a) and CAD/CAM milling (b). Co–Cr, cobalt–chromium.

Figure 3



Scanning electron microscope figure of Co–Cr alloys at 2000x after sandblasting/cast (a), sandblasting/CAD/CAM milling (b). Co–Cr, cobalt–chromium.

untreated sample to a great extent, whereas sandblasted CAD/CAM milled Co–Cr sample revealed major changes from the untreated sample. It showed substantial microchanges in the surface texture with increased irregularities resembling the dendritic pattern of the cast sandblasted sample (Fig. 3a and b).

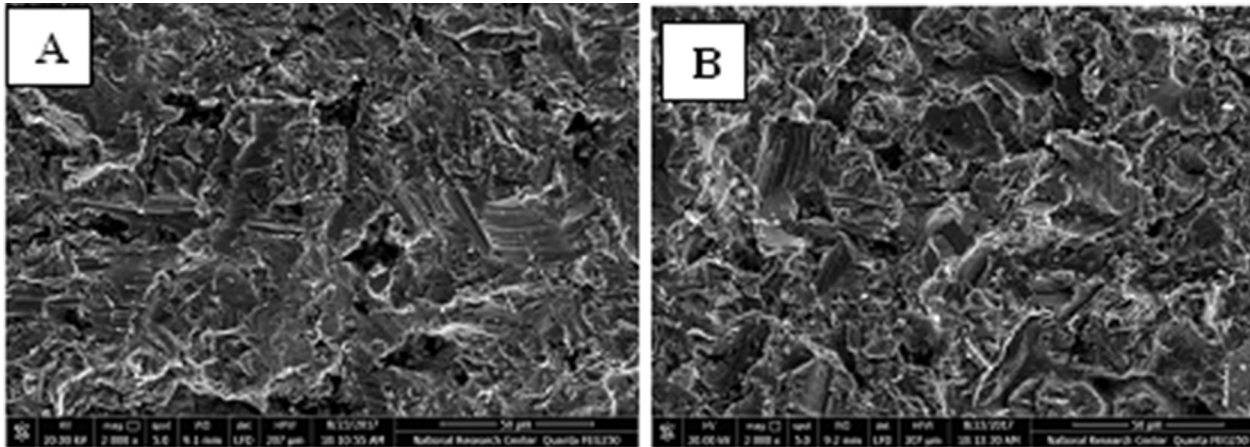
- (2) Oxidation: oxidized sample of cast Co–Cr exhibited a dendritic pattern that is comparable to the untreated and sandblasted samples. On the contrary, oxidized CAD/CAM milled Co–Cr sample showed extensive microchanges in the surface texture and increased irregularities, and its pattern is comparable to that of the oxidized cast sample (Fig. 4a and b).
- (3) Laser etching: SEM picture of laser-etched cast Co–Cr sample exhibited significant changes in the

form of smooth pitted areas surrounded by tiny fissures and narrow microcracks with some voids and decreased surface irregularities. However, the laser-etched CAD/CAM milled Co–Cr sample was characterized by smooth areas surrounded by minimal microcracks with fusion of the grain boundaries in the most superficial layer and decrease in the isolated micro porosity that were present in the untreated sample. Laser-etched SEM image of CAD/CAM milled Co–Cr appeared to be relatively smoother than other surface treatments (Fig. 5a and b).

Failure mode analysis results

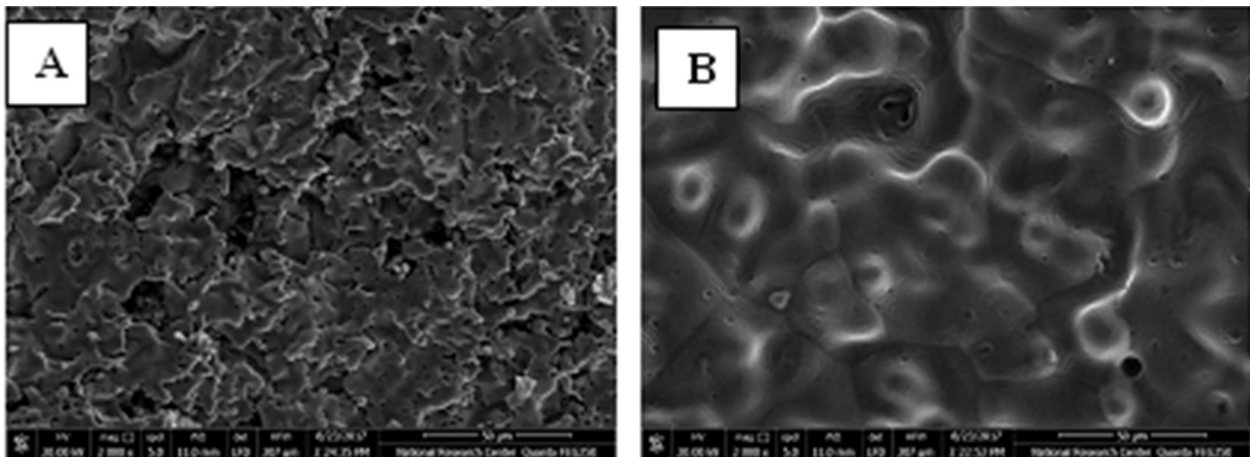
With both fabrication techniques, all subgroups exhibited cohesive failure mode within the porcelain,

Figure 4



Scanning electron microscope figure of Co–Cr alloys at 2000x after oxidation/cast (a), and oxidation/CAD/CAM milling (b). Co–Cr, cobalt–chromium.

Figure 5



Scanning electron microscope figure of Co–Cr alloys at 2000x after laser etching/cast (a), and laser etching/CAD/CAM milling (b). Co–Cr, cobalt–chromium.

except for the laser etching subgroups, which showed mixed failure mode (Fig. 6a–d).

Discussion

Porcelain-fused-to-metal restorations are widely accepted dental restorations because they combine the advantages of both metal and ceramics [1–3]. Because of the speed-up production and cost effective, CAD/CAM soft milling/postsintering technique can be used as an alternative to the traditional casting technique for fabrication of the metallic part of metal ceramic restorations [6].

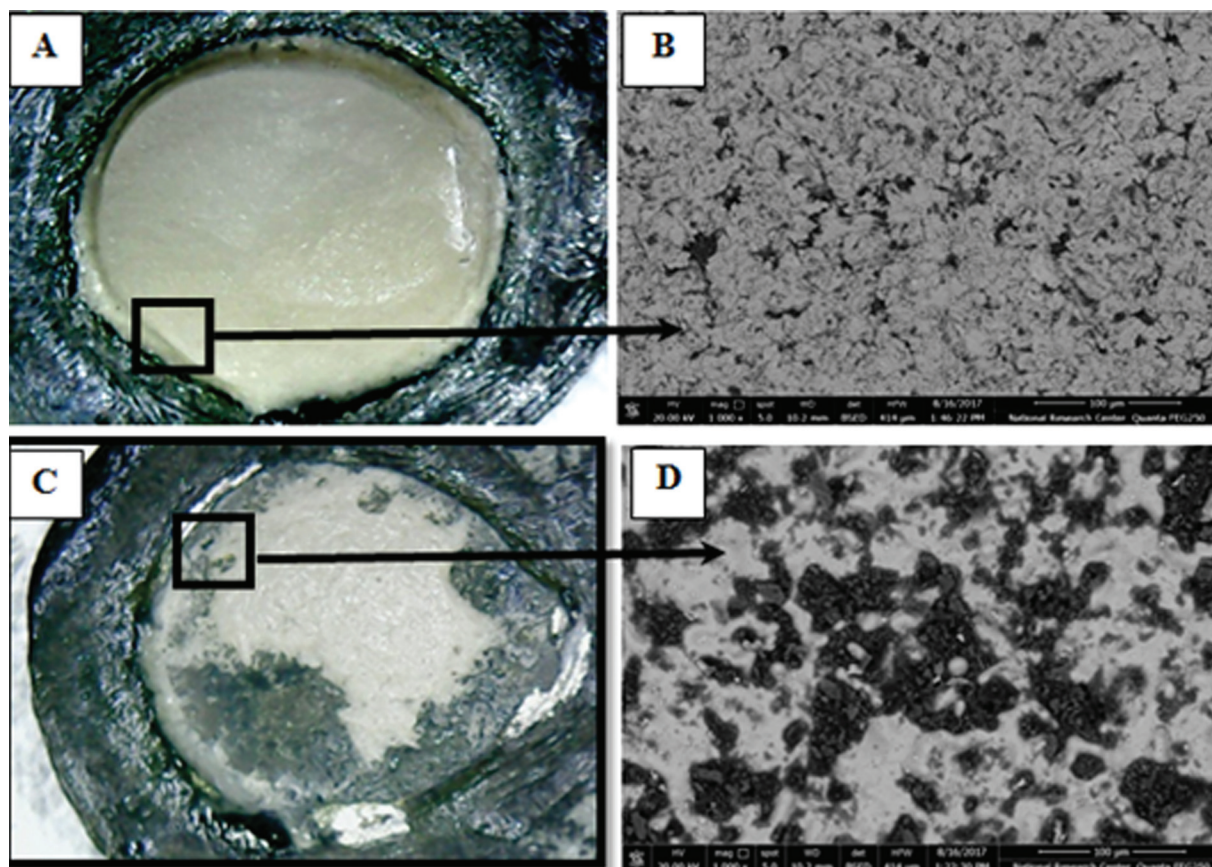
Persistent bond at the metal ceramic junction leads to prosperity of metal ceramic restoration. In the literature, there is no ideal method for assessment of the bond strength between metal and porcelain [29].

Many authors utilized the shear test to measure this bond [9–11]. The shear test is exceptionally dependable, because it relies on the least experimental variables and constitutes less residual stress at the metal–ceramic junction [16–18], and also oblique forces are decreased [13,18,24]. Therefore, the SBS test was used in the present study.

This study evaluated SBS between porcelain and CAD/CAM milled Co–Cr alloy treated by sandblasting, oxidation, and laser etching in comparison with treated by cast alloy.

On the basis of the results of our research, the first null hypothesis which stated that alloy fabrication technique had no effect on SBS between porcelain and milled as well as cast Co–Cr alloys was accepted. Statistically insignificant difference was

Figure 6



Representative samples of sandblasting and oxidation subgroups (a and b), showing cohesive failure mode within the porcelain and laser-etching subgroups (c and d), showing mixed failure mode.

observed among the two tested fabrication techniques regarding SBS.

Bonding of porcelain to metal relies on mechanical interlocking, chemical bonding, and Van der Waals forces. The mechanical bond depends mainly on the surface texture of the metal; the chemical bond is attained through the oxide layer, whereas the Van der Waals force has only a small role in the bond strength. Alloy fabrication technique and their surface treatment greatly affecting the final surface texture of the alloys [4,5,30]. The surface architecture of the two tested alloys was different just after casting and milling before any surface treatment. The insignificant difference between the two fabrication techniques is probably because, after sandblasting with $110\mu\text{m}$ Al_2O_3 , the two Co–Cr alloys had comparable morphologies and because after heat treatment they had comparable oxidation properties, resulting in similar mechanical and chemical bonds [15].

These results were in agreement with Lee *et al.* [10], Serra-Prat *et al.* [13], Li *et al.* [15], and Rosenstiel *et al.*

[30] who demonstrated that Co–Cr alloy fabrication technique had no effect on its bond strength with ceramics. Co–Cr alloys fabricated with recent techniques exhibited metal-ceramic bond strength comparable to that of castable alloy.

However, the results of this study contradict those of Wang *et al.* [8] and Mhaske Prasad *et al.* [9], who demonstrated that fabrication technique significantly affected the bond strength between porcelain and base metal alloys and mentioned that alloys fabricated by contemporary techniques are better than those fabricated by conventional casting. These contradictions in results may be owing to the methodological differences, as they compared Co–Cr alloys fabricated by casting with those fabricated by computer numerical control milling and selective laser melting techniques.

Alloy surface treatment statistically significantly affected the SBS values registered in this study, supporting the rejection of the second null hypothesis, which stated that Co–Cr surface treatments would not affect SBS.

The results of this research indicated that the SBS was affected by the Co–Cr surface treatment. Similar results were reported by many authors who revealed the remarkable influence of alloy surface treatment on bond strength with veneering porcelain [16–18,31]. Conversely, the results were inconsistent with other researchers [19,23–25]. These inconsistencies can be related to different surface treatment protocols followed in the research studies and dissimilar base metal alloys tested.

Despite the fact that there was an insignificant difference between sandblasting and oxidation, there are still numerical differences that deserve to be discussed. Sandblasting recorded the highest SBS values among the tested surface treatments regardless of the fabrication technique. Sandblasting with 110 μg Al_2O_3 led to substantial changes in the surface texture with increased surface irregularities of both alloys, specially the milled one, as showed in SEM. Similar result was found in a study carried out by Kunt *et al.* [26] who concluded that base metal alloys were maximally roughened by sandblasting than the other tested surface treatments. Rough surfaces of metal substrate are reported to encourage the wetting ability of ceramic superior than smooth surfaces, which results in enhanced metal–ceramic bond strength. Metal surface roughness provides the micromechanical retention that occurs as the ceramic move onto the irregularities of metal surface, thereby enhancing the metal–ceramic bonding. Furthermore, metal surface roughness improves the bond strength by enlarging the bonding surface area. It was demonstrated that metal–ceramic bond strength is greatly enhanced by sandblasting the metal surface with 50 and 110 μg Al_2O_3 [16,17,32].

The results are consistent with those of other studies, which mentioned that sandblasting improved the SBS among different surface treatments [16,17]. On the contrary, Deepak *et al.* [18] found that laser surface treatment produced an outstanding surface roughness and attained better SBS values than sandblasting. Variation in results may be referred to the different sandblasting protocols used in both studies; they used Al_2O_3 with 50 μm particles size, whereas our study used 110 μm .

Irrespective of fabrication technique, oxidation surface treatment results were insignificantly different from those of sandblasting. These results may be explained by the fact that both alloys had similar oxidation properties, so after heating, comparable chemical bonds result [15]. After oxidation cycle, samples of

both alloys were subjected to sandblasting by 110 μg Al_2O_3 , as recommended by the manufacturer. This sandblasting procedure gave rough surface texture to the oxidized samples that resembled that of the sandblasted subgroups. The SEM images supported these results, as both sandblasted and oxidized samples showed similar morphological patterns. Opposite to our findings, some researchers mentioned that oxidation heat treatment had no significant effect on SBS [19,23]. This contradiction may be because they used different oxidation protocols than the used in this study. George [33], in his laser review, mentioned that laser-etching controls microtopography more readily because it is of depth penetration, depending on the material irradiated, and gives increased surface roughness without contamination and a steady surface morphology [33]. In the present study, laser surface treatment with both tested alloys recorded the lowest SBS values among the tested surface treatments, and this was consistent with its SEM images, which showed the smoothest surface texture among the tested surface treatments, and the used laser parameters did not roughen the metal surface. Spohr *et al.* [34] showed that the discharge of laser energy encouraged the subsequent surface changes: material removal owing to the punctate nature of laser-induced microexplosions, resulting in the formation of voids, and fusing and melting of the most superficial layer. The results of this study were in harmony with those of Moslehifard *et al.* [17]. However, it disagreed with other authors, as they used different laser parameters [18]. Complementary study should be performed to test the effectiveness of different laser parameters in roughening the surface of Co–Cr alloys to improve its bond strength to porcelain.

Irrespective of fabrication technique, sandblasting and oxidation subgroups showed cohesive failure mode within the porcelain. On the contrary, the laser-etching subgroups showed mixed failure mode. Cohesive failure mode within the porcelain is the most desirable failure mode, indicating that the metal–porcelain bond was stronger than that within porcelain and that more destructive force was needed to separate the metal and porcelain [35]. This failure mode was in agreement with the high SBS values and SEM images of sandblasting and oxidation subgroups. In laser subgroups, part of the failure mode was cohesive within the porcelain, whereas the other was adhesive at the metal–porcelain interface, which means that the bond strength in some areas was not strong enough, and this was consistent with the SBS values and SEM images. Many researchers registered cohesive failure mode [8,14,18], whereas others registered mixed one [9,10,16].

According to ISO Standard 9693, which stated that an adequate bond between metal alloy and ceramic occurs when the bond strength is higher than 25 MPa [36], all SBS values recorded in this study were clinically acceptable.

The study had the following limitations: the SEM used was inadequate for measuring the oxide thickness in oxidation surface treatment subgroups. Thus, radiographic photoelectron spectroscopy should be used to quantify the oxide thickness and identify the type of oxide on the Co–Cr alloy surface. Moreover, only one recent fabrication technique of Co–Cr alloy was tested and compared with conventional casting. In addition, clinical trials are needed to substantiate the in-vitro testing.

Conclusions

Based on the results of this in-vitro study, the following conclusions were drawn: bond between surface treated Co–Cr alloys and porcelain is independent of the fabrication technique, laser etching recorded the least SBS among the tested surface treatments irrespective of the fabrication technique, and all SBS values recorded in the present study were clinically acceptable.

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Conflicts of interest

There are no conflicts of interest.

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