THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Marginal fit of metal-ceramic crowns fabricated by using a casting and two selective laser melting processes before and after ceramic firing

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ABSTRACT

Statement of problem. Few studies have investigated changes in the marginal fit of metal-ceramic restorations fabricated by selective laser melting (SLM) techniques after the application of veneering ceramic.

Purpose. The purpose of this in vitro study was to evaluate the marginal fit (silicone replica technique) and internal porosity (cross-section analysis) of cobalt-chromium (Co-Cr) alloy metal crowns prepared by using 2 SLM processes together with a casting technique before and after ceramic veneering.

Material and methods. Cast single Co-Cr crowns and SLM-processed crowns with large (SLML) or small (SLMS) porosity were prepared (n=20/group), and half were subjected to ceramic veneering. On a single Co-Cr master die, the marginal discrepancy (MD) and absolute marginal discrepancy (AMD) of the crowns were measured by using the silicone replica technique, in which each replica was cut into 4 sections before and after ceramic veneering (n=10 for each subgroup). After marginal fit measurements, each metal coping was cross-sectioned into 4 parts, and 5 rectangular optical microscope images were acquired on both outer corners of each quarter. The porosity was then calculated as the ratio of the black-to-white pixels on the binarized images. The data were analyzed by 2-way ANOVA and the post hoc test (Tukey or Student *t* test) (α=.05).

Results. Before ceramic veneering, the 2 SLM groups showed significantly larger MDs than the casting group (56.4 ±10.4 μm) (P<.05). A significant increase in MD after ceramic veneering was detected only in the SLML group (P<.001). The AMD values showed a similar trend with MD values. The 2 SLM groups (in particular, SLML) showed a significantly higher amount of porosity than the casting group before ceramic veneering (P<.001). Only the SLML group showed a significant decrease in the amount of porosity after ceramic veneering (P<.001).

Conclusions. Within the limitations of this in vitro study, large internal porosity within the SLM-fabricated Co-Cr metal copings affected the marginal fit of the metal-ceramic crowns. However, all the MD values of the 3 groups were lower than the acceptable range even after the application of veneering ceramic. (J Prosthet Dent 2019;122:475-81)

Metal-ceramic restorations are still a popular and excellent choice for fixed partial dentures because of their esthetic and mechanical properties.[1,2] The alloys most commonly used as metal substructures for metal-ceramic restorations are nickel-chromium (Ni-Cr) and cobalt-chromium (Co-Cr).[1,3] Co-Cr alloys are preferred for patients who are allergic to nickel.[1,3] However, the casting of Co-Cr alloys is difficult because of their high melting point, high hardness, and low ductility.[4] Moreover, accumulated errors are inevitable in the series of laboratory procedures during casting.[5]

In the last decade, computer-aided design and computer-aided manufacturing (CAD-CAM) technology in dentistry has emerged as an alternative to traditional casting to produce dental metal prostheses.[1-3,5-10] Co-Cr prostheses are fabricated by using 2 main CAD-CAM–based processes: subtractive and additive manufacturing.[10,11] The hard milling process for Co-Cr alloys, one of the subtractive processes, is difficult because of the high hardness of the solid blank.[1,12] Selective laser melting (SLM), one of the additive manufacturing techniques, fabricates metallic structures by fusing fine layers of metal powder by means of

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Republic of Korea (2017R1A6A3A11036498).

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Clinical Implications

The fabrication of high-quality selective laser melting metal frameworks with minimal porosity seems essential in achieving metal-ceramic restorations with a better marginal fit.

a focused laser beam.[10,13,14] These new CAD-CAM–based techniques are considered promising alternatives to traditional casting.[3]

Marginal discrepancy (MD) is one of the most important factors in the success and longevity of metal-ceramic restorations.[1,3,6] Insufficient marginal adaptation can accelerate plaque accumulation and increase the risk of secondary caries and microleakage.[1,3,15] A clinically acceptable MD value has been reported to be below the range of 100 μm to 120 μm.[3,16-18] A recent study reported that the marginal fit of Co-Cr dental alloys depends on the fabrication technique.[3] In addition, the fit of the Co-Cr metal framework in metal-ceramic restorations may deteriorate during the firing cycles used for ceramic application, depending on the framework design, alloy type, ceramic shrinkage during firing, and the difference in thermal expansion for ceramic and alloy.[1,19] Kocaağaoğlu et al[1] reported that the application of veneering ceramic significantly increased the MD of SLM-fabricated Co-Cr alloy copings but not those of cast and hard-/soft-milled ones. However, their study provided no direct evidence to support their findings.

The purpose of this in vitro study was to evaluate the marginal fit of Co-Cr alloy copings prepared by 3 different manufacturing processes (2 SLM together with 1 casting) before and after the application of veneering ceramic. Preliminary tests detected noticeable changes in the porosity pattern in the sectioned metal copings before and after ceramic veneering. In this study, therefore, 2 different SLM alloys with large (SLML) and small (SMLS) porosity were prepared by adjusting the laser process parameters, and amounts of internal porosity of the 2 alloys, together with the cast alloy, were compared on the sectioned images.[20-24] The first null hypothesis was that no significant differences would be found in the marginal fit of nonveneered metal crowns prepared by the 3 different manufacturing processes. The second null hypothesis was that the ceramic veneering would not change the marginal fit of the restorations nor the amount of internal porosity of the metal copings.

MATERIAL AND METHODS

Single Co-Cr metal copings were prepared by 3 different processes (1 casting and 2 SLM groups; n=20 for each group), half of them being subjected to ceramic veneering (n=10 for each subgroup) (Fig. 1). From preliminary tests, the sample size was determined with a power analysis to provide statistical significance (α=.05) at 80% power.[3] The 3 manufacturing processes and corresponding Co-Cr alloys and devices used are summarized in Table 1. All the following laboratory processes, including the ceramic veneering process, were performed by a single experienced dental technician.

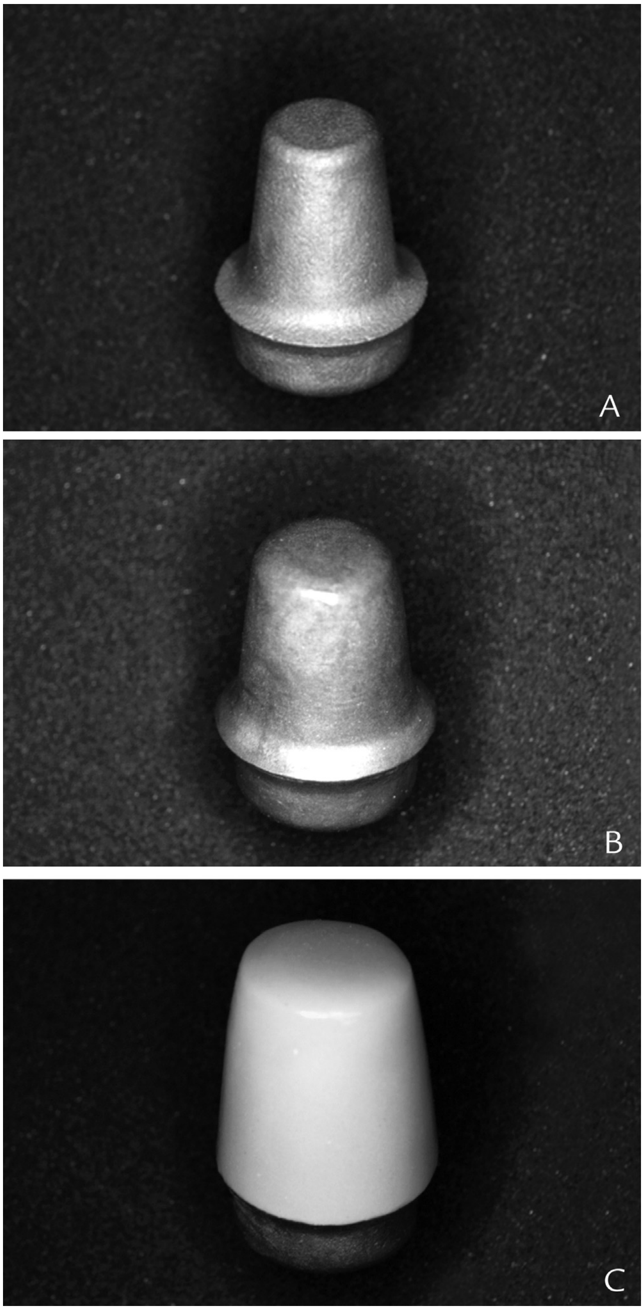

Figure 1. Procedure for preparation of die, crowns, and metal-ceramic crowns. A, Standardized Co-Cr die. B, Metal crown seated on original master die. C, Metal-ceramic crown seated on original master die. Co-Cr, cobalt-chromium alloy.

Table 1. Three manufacturing processes and the corresponding Co-Cr alloys and devices used

Manufacturing Process	Co-Cr Alloy (Manufacturer)	Composition (wt%)*	Device (Manufacturer)	Laser Process Parameter
Casting	StarLoy C (DeguDent)	Co 59.4, Cr 24.5, W 10, Nb 2, V 2, Mo 1, Si 1, Fe 0.1	Centrifico (Kerr Corp)	Not applicable
Selective laser melting, large porosity (SLML)	remanium star CL (Dentaurum GmbH & Co KG)	Co 60.5, Cr 28, W 9, Nb<1, Si 1.5, Fe<1, Mn<1	M1 (Concept Laser GmbH)	Laser power: 100 W; scan speed: 90 mm/s; scan-line spacing: 0.15 mm
Selective laser melting, small porosity (SLMS)				Laser power: 200 W; scan speed: 128.6 mm/s; scan-line spacing: 0.10 mm

*As provided by manufacturers.

A mandibular premolar with a height of 6.25 mm, a finish line width of 1.0 mm, and an occlusal convergence of 6 degrees was prepared.[3] A master die was cast with a Co-Cr alloy (StarLoy C; DeguDent) from a 3D printed wax pattern (VisiJet M3 Dentcast; 3D Systems) by using a casting machine (Centrifico; Kerr Corp).[3]

In the casting groups, the wax patterns (LunaCast; ACF GmbH) were prepared on the metal die, invested, and cast following the same procedures described for the die fabrication. In the SLM groups, a virtual die model was created by imaging the die by using a scanner (D700; 3Shape A/S), and a metal coping with a thickness of 0.4 mm was designed on the model by using a CAD software program (DentalDesigner; 3Shape A/S).[3] Metal copings were fabricated based on the CAD data by using an SLM device (Concept Laser M1; Concept Laser GmbH) with a laser spot size of 0.08 mm. In the metal coping fabrication, 2 different types of specimens with large (SLML) and small (SLMS) porosity were prepared by intentionally adjusting 3 laser process parameters (laser power, scan speed, and scan-line spacing) (Table 1).[25] The powder was applied to a plate and laser-melted upward in subsequent layers after a 30-μm-thick layer was completed.

The metal copings belonging to a group (n=20) were divided into 2 groups, and half of them were additionally veneered with a feldspathic ceramic (VITA VM13; VITA Zahnfabrik) according to the manufacturer's instructions (Table 2). One of the copings was subjected to ceramic veneering, and a 2-piece silicone mold was prepared from the metal-ceramic crown.[1] The silicone mold was used to standardize the other ceramic veneers.[1]

The marginal fit of the nonveneered and veneered crowns was measured by the silicone replica technique on a single master die.[1,7-9] To evaluate the marginal fit, MD and absolute marginal discrepancy (AMD) were measured.[3,26] MD was defined as the distance from the abutment margin to the metal coping in a straight line.[3,8] AMD was defined as the distance from the edge of the metal coping to the abutment margin.[3,8] Each crown was filled with light-body silicone impression material (Aquasil Ultra; Dentsply Sirona), placed onto the abutment tooth, and then loaded with 50 N in the apical direction until the material polymerized.[7] After the crown was removed from the die, the material was stabilized with a contrasting medium-body silicone impression material (Aquasil Ultra; Dentsply Sirona).[7] The silicone replica was sectioned into 4 parts by 2 cuts each in the mesiodistal and buccolingual directions.[9] Each of these 2 directions was measured for every part, yielding 8 measurements,[9] by using a microscope (SMZ1500; Nikon Corp) at ×160 magnification (Fig. 2A).[7] The MD or AMD value of each crown was recorded as the average of all 8 measurements.

Table 2. Firing parameters of veneering ceramic VM13

Firing Parameters	Start (°C)	Predry (min)	Heat (min)	Heat Rate (°C/min)	Fire (°C)	Hold (min)	Vacuum Hold (min)
Oxidation	600	3	4	75	900	2	4
Opaque	500	2	5.12	75	890	1	5.12
Dentin (first)	500	6	6.55	55	880	1	6.55
Dentin (second)	500	6	6.44	55	870	1	6.44
Glaze	500	–	4.45	80	880	2	–

After the marginal fit measurements, the metal copings were embedded in epoxy resin (EpoFix Resin; Struers A/S) and sectioned into 4 parts by 2 cuts each in the mesiodistal and buccolingual directions by using a slow-speed diamond saw (IsoMet; Buehler Ltd). Specimens were polished by using SiC papers up to #2000 grit and then with 6-, 3-, and 1-μm diamond paste (Buehler Ltd). Five rectangular optical microscope images (×50) were acquired on both outer corners of each quarter (a total of 8 measurements per specimen; Fig. 2B).[9] Each original image was then binarized by using a threshold value with the ImageJ software (National Institutes of Health).[21] The amount of porosity was then quantified as the ratio of the black-to-white pixels, representing the fraction of the surface voids over the total surface.[21]

After being examined for normal distribution (Shapiro-Wilk test) and equal variances (Levene test), the results were analyzed with 2-way ANOVA (2 variables: manufacturing techniques and ceramic veneering) and post hoc analysis (Tukey or Student *t* test) (α=.05). The porosity data were $\log_{10}$+1-transformed before analysis to provide variance homogeneity. The statistical analyses were carried out by using a statistical software program (SPSS Statistics v17.0; SPSS Inc).

RESULTS

The means ±standard deviations (SDs) of the MD and AMD values for the 3 groups before and after ceramic

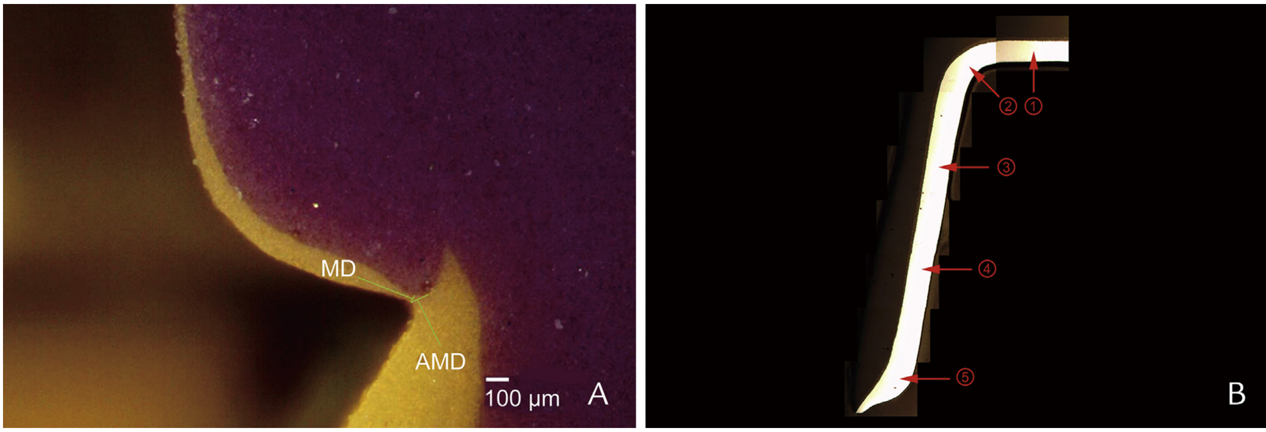

Figure 2. A, Sectioned silicone replica, showing marginal discrepancy (MD) and absolute marginal discrepancy (AMD) measurements (*orange*, light-body silicone impression material; *purple*, medium-body silicone impression material). B, Sectioned metal coping (after ceramic veneering). Rectangular images (×50) acquired from 5 points (*arrows*) for porosity analysis.

Table 3. Mean ±standard deviation marginal discrepancy (µm) and absolute marginal discrepancy (µm) in 3 groups (n=10)

Manufacturing Process	Before Ceramic Veneering	After Ceramic Veneering
Marginal discrepancy		
Casting	56.4 ±10.4[a1]	61.0 ±12.7[a1]
SLML	76.0 ±9.6[b1]	98.5 ±12.2[b2]
SLMS	74.8 ±15.9[b1]	70.1 ±13.8[a1]
Absolute marginal discrepancy		
Casting	118.0 ±17.2[a1]	126.1 ±16.1[a1]
SLML	143.6 ±10.4[b1]	173.1 ±21.5[b2]
SLMS	141.2 ±15.9[b1]	135.3 ±25.9[a1]

SLML, selective laser melting-large porosity; SLMS, selective laser melting-small porosity. Same lowercase letters show no significant differences among 3 manufacturing processes (Tukey test, *P*>.05). Same numbers show no differences between before and after ceramic veneering (Student *t* test, *P*>.05).

Table 4. Results of 2-way ANOVA for marginal discrepancy and absolute marginal discrepancy data

Factor	Type III Sum of Squares	*df*	Mean Square	F	*P*
Marginal discrepancy					
Manufacturing process	8142.810	2	4071.405	25.550	<.001
Ceramic veneering	837.761	1	837.761	5.257	.026
Manufacturing process×ceramic veneering	1919.766	2	959.883	6.024	.004
Absolute marginal discrepancy					
Manufacturing process	13 194.044	2	6597.022	19.311	<.001
Ceramic veneering	1672.704	1	1672.704	4.896	.031
Manufacturing process×ceramic veneering	3195.277	2	1597.639	4.677	.013

veneering are summarized in Table 3. The Shapiro-Wilk test showed that all the groups had *P*>.05, which means all the data sets were in normal distribution. In addition, the Levene test revealed that the assumption of equal variances was met for both MD (*P*=.774) and AMD (*P*=.056) values. Both the manufacturing process and ceramic veneering significantly affected the MD and AMD (*P*<.05) (Table 4), and the 2-way ANOVA also showed a significant interaction between the 2 variables (*P*<.05). The data were stratified and analyzed by using 1-way ANOVA and the Student *t* test to determine whether the differences in the values were significant. The Tukey post hoc analysis showed that the SLML (76.0 ±9.6 µm) and SLMS (74.8 ±15.9 µm) groups showed significantly larger MD values than the casting group (56.4 ±10.4 µm) (*P*<.05). The 2 SLM groups before ceramic veneering exhibited statistically similar MD (*P*=.977). A significant increase in MD after ceramic veneering was detected only in the SLML group (*P*<.001). The AMD values for the casting group were 118.0 ±17.2 µm before ceramic veneering and 126.1 ±16.1 µm after ceramic veneering. Before ceramic veneering, the 2 SLM groups exhibited significantly larger AMD values than the casting group (*P*<.05). A significant increase in AMD after ceramic veneering was found only in the SLML group (*P*=.002).

Figure 3 shows the binary images acquired on the sectioned surfaces for the 3 groups. The means ±SDs of the porosity for the 3 groups before and after ceramic veneering are also presented in Table 5. The Shapiro-Wilk test showed that all the groups had *P*>.05. However, the assumption of equal variances was broken by the Levene test (*P*<.001). The 2-way ANOVA of the porosity data was conducted with the transformed data because the assumption of equal variances was successfully met after $\log_{10}$+1-transformation (Levene test, *P*=.403). The 2-way ANOVA revealed that the manufacturing technique (*P*<.001), ceramic veneering (*P*<.001), and interaction between these two variables (*P*<.001) all significantly affected the amount of porosity (Table 6). A significant increase in porosity after ceramic veneering was detected only in the SLML group (*P*<.001), which showed the highest porosity among the 3 groups before ceramic veneering (*P*<.001).

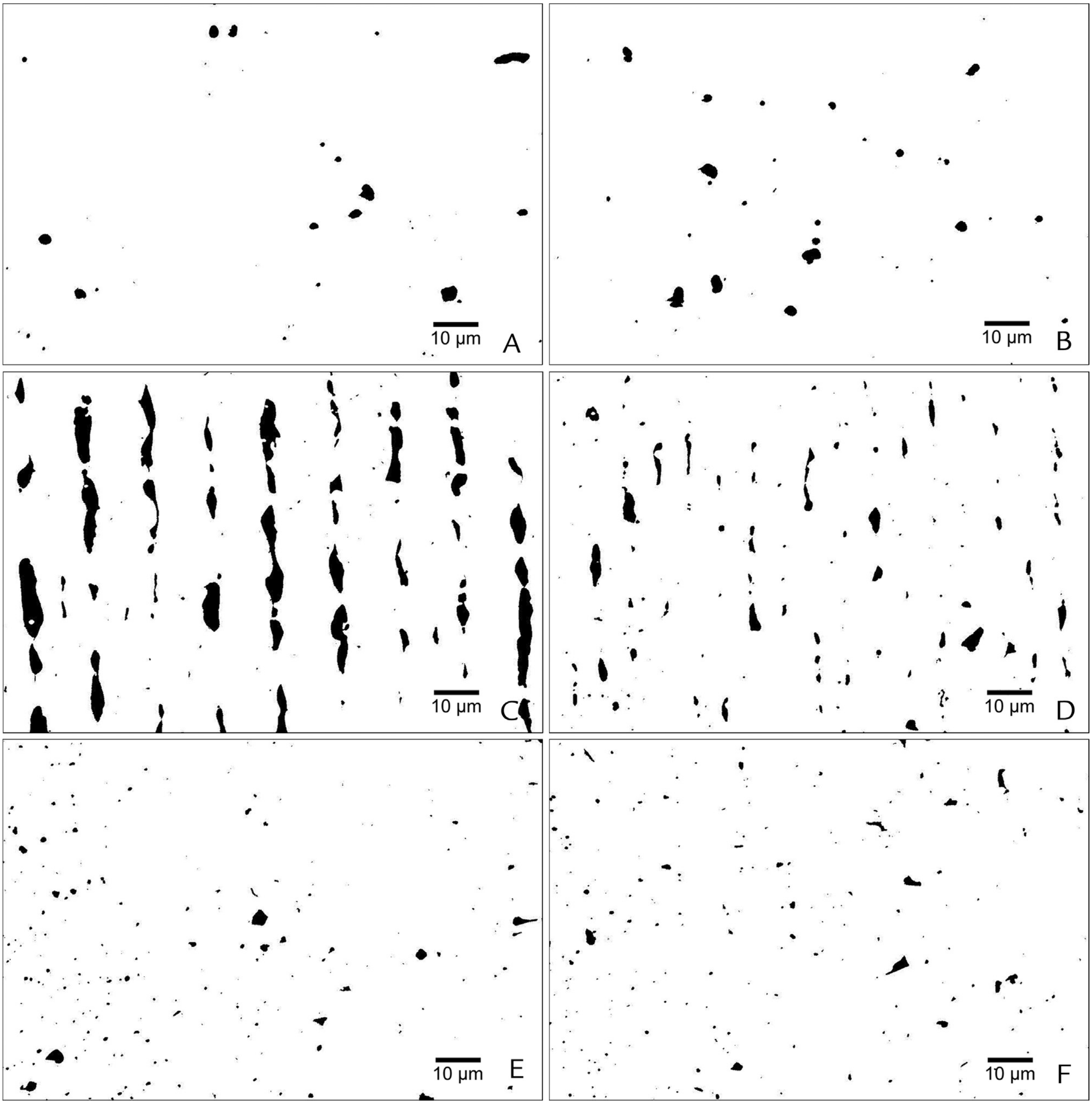

Figure 3. Representative binary images (×250) showing changes in porosity on sectioned metal copings before and after ceramic veneering. A, B, Casting. C, D, Selective laser melting-large porosity. E, F, Selective laser melting-small porosity. A, C, E, Before ceramic veneering. B, D, F, After ceramic veneering.

DISCUSSION

A good marginal fit is one of the most clinically important factors for the long-term success of metal-ceramic restorations.[1,3,6,15] In this in vitro study, Co-Cr alloy copings were fabricated by 3 different manufacturing processes (Table 1) and then subjected to ceramic veneer firing (Table 2) to evaluate potential changes in the marginal fit (MD and AMD) of the restorations during the firing process (Figs. 1, 2). The first null hypothesis was rejected because significant differences were found among the nonveneered metal copings produced by the 3 different processes (Table 3). The second null hypothesis, that the ceramic veneering would not change the marginal fit or the amount of internal porosity, was partially rejected because significant changes in the values were noted in the SLML group after ceramic veneering (Fig. 3, Tables 3 and 5).

In the present study, the marginal fit of the metal copings was examined by the silicone replica method

Table 5. Mean ±standard deviation porosity (%) calculated from binary images of sectioned metal surfaces in 3 groups (n=10)

Manufacturing Process	Before Ceramic Veneering	After Ceramic Veneering
Casting	0.66 ±0.08[a1]	0.72 ±0.11[a1]
SLML	8.34 ±1.46[b1]	3.81 ±0.93[b2]
SLMS	0.97 ±0.16[c1]	0.85 ±0.18[a1]

SLML, selective laser melting-large porosity; SLMS, selective laser melting-small porosity. Same lowercase letters show no significant differences among 3 manufacturing processes (Tukey test, $P>.05$). Same numbers show no differences between before and after ceramic veneering (Student *t* test, $P>.05$).

Table 6. Results of 2-way ANOVA for porosity data

Factor	Type III Sum of Squares	*df*	Mean Square	F	*P*
Manufacturing process	9.767	2	4.883	739.756	<.001
Ceramic veneering	0.229	1	0.229	34.698	<.001
Manufacturing process×ceramic veneering	0.393	2	0.196	29.752	<.001

(Fig. 2A) because this method is nondestructive and has high reliability and precision.[7,8] Preliminary micro-computed tomography (μCT) tests of the Co-Cr crowns showed a low capacity for discrimination, insufficient to characterize their internal porosity.[3,26] Therefore, the internal metal porosities before and after ceramic veneer firing were destructively investigated by using the binary images of the sectioned surfaces (Fig. 3).

Before ceramic veneering, the casting group showed better marginal fit than the 2 SLA groups, consistent with the findings of Kocaağaoğlu et al[1] and Kim et al.[3] However, the MD values of the 2 SLM groups before ceramic veneering were still lower than the acceptable range of 100 μm to 120 μm.[16] A significant increase in the marginal fit after ceramic veneering was found only in the SLML groups (Table 3), which generally corresponds with a recent investigation by Kocaağaoğlu et al.[1] The distortion of the marginal fit during the firing cycles has been accounted for by several factors, such as ceramic firing shrinkage and the difference in thermal expansion between the ceramic and alloy.[1,19] Metal copings subjected to high-temperature conditions during firing cycles (Table 2) may cause dimensional change or distortion, eventually reducing the marginal fit of metal-ceramic restorations.

In the SLM technique, full local melting and rapid solidification may minimize the porosity and produce a homogeneous and almost completely dense material.[10,13] However, the development of porosity in SLM alloys greatly depends on the adjustment of operating conditions, including various laser process parameters.[10,13,14,25] In the SLMS group, the 3 parameters were set up to be as optimal as possible to fabricate dense metal copings with minimal porosity (Table 1, Fig. 3). In the SLML group, the energy density of the applied laser was lowered by altering the process parameters for less optimality to induce insufficient fusion of the metallic powders during melting. Thus, SLML metal copings with a less dense structure and large porosity were achieved.[25]

The sectioned images of the metal copings of the 3 groups showed some pore formation within the metal framework (Fig. 3). The casting groups exhibited the formation of spherical closed pores, which were isolated from each other and surrounded by the material wall.[20] Although porosity is a well-known limitation of cast structures,[13] the porosity of the casting group was lower than that of the SLM groups (Table 5), with the value not significantly changing even after ceramic veneering. On the contrary, the SLML groups (in particular, the SLML group) showed the formation of open pores connected to each other (interconnected) and to the material surface.[20] In the SLML group, most of the elongated, narrow crack-like voids were oriented perpendicularly to the building direction (Fig. 3E). These defects seem to result from binding faults (lack of fusion), probably because of incomplete melting of the powders due to insufficient energy density.[13,14,22] It was assumed that the volume fraction of such large defects decreased during ceramic veneer firing, which acted like post-heat treatment (Table 2),[23] eventually changing the dimension and marginal fit of the metal-ceramic crowns. However, this assumption requires further validation through subsequent investigation.

The findings of this in vitro study suggest that SLM laser process parameters should be optimized to minimize porosity formation in metal copings and prevent potential changes in the marginal fit of metal-ceramic restorations. Although a significant increase was found in the marginal fit in the SLML group, all the MD values in the 3 groups were lower than the acceptable range even after the application of veneering ceramic.[16] In this study, a nondestructive method (silicone replica technique) and a destructive method (section analysis) were combined to evaluate the marginal fit and internal porosity of the Co-Cr alloy copings. Recently, improved μCT techniques, such as synchrotron-based μCT, which may offer an improved level of detail, larger penetration, and enhanced resolution, have been used for the defect characterization of metals.[24] Such new techniques will enable completely nondestructive evaluation of the marginal fit and internal porosity of metallic restorations.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Among the 3 groups (casting, SLML, and SLMS), only the SLML group showed a significant increase in marginal fit and a significant decrease in porosity after the application of veneering ceramic.
2. All the MD values of the 3 groups were lower than the acceptable range even after the application of veneering ceramic.

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https://doi.org/10.1016/j.prosdent.2019.03.002