THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Effect of internal design changes on the mechanical properties of laser-sintered cobalt-chromium specimens

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ABSTRACT

Statement of problem. Changing the internal design of a metal framework may decrease the manufacturing time, the weight of the restoration, and the amount of alloy powder used, as well as simplify the fabrication process.

Purpose. The purpose of this in vitro study was to evaluate the effect of framework internal design changes on the mechanical properties of cobalt-chromium (Co-Cr) specimens manufactured by using direct metal laser sintering (DMLS).

Material and methods. Dumbbell-shaped test specimens were designed as per the International Organization for Standardization (ISO) 22674(E) standard by using a 3-dimensional software program. A total of 70 dumbbell-shaped specimens were prepared by using Co-Cr alloy powder and DMLS (n=10). The control group specimens were solid with the internal completely filled. For the test groups, the internal design of the dumbbell-shaped specimens was modified. Leaving the outer shell thickness of the specimens at 0.5 mm for all test groups, 6 different internal designs were created, and the specimens were weighed. The tensile strength test was used to evaluate the mean peak strength, elastic modulus, and percentage elongation of the specimens. One-way ANOVA followed by the Dunnett T3 test was used for statistical analysis (α=.05).

Results. A statistically significant difference was found among the groups in terms of bar weight and peak strength (P<.05). The highest values were observed in the control group for all evaluated parameters (mean ±standard deviation bar weight: 1321.3 ±36.6 mg, peak strength: 1045 ±36.7 MPa, elastic modulus: 284.2 ±71.9 GPa, and elongation: 28.7 ±7%). However, no statistically significant difference was observed for elastic modulus or percentage of elongation (P>.05).

Conclusions. Decreasing the weight of the frameworks by changing the internal design of the specimens also decreased the peak strength. However, it did not affect the elastic modulus or the percentage of elongation. (J Prosthet Dent 2021;■:■-■)

Metal-ceramic fixed partial dentures are reliable prostheses, especially in high-stress-bearing areas, and are still considered the restoration of choice for long-span prostheses.[1,2] Various methods have been described for fabricating the metal frameworks for metal-ceramic restorations,[3] including direct metal laser sintering (DMLS), popular because it produces frameworks with excellent mechanical properties and low processing costs.[2-12]

When an edentulous patient with severely resorbed alveolar ridges is rehabilitated with complete-arch implant-retained fixed partial dentures (IRFPDs), the restoration needs to replace the natural teeth and the soft tissues.[13] This type of restoration is classified as Type 3 IRFPD.[13] Whether it is a metal-acrylic resin or metal-ceramic restoration, the metal framework should comprise the body of the restoration so that the thickness of the esthetic material can be controlled.[14,15] However, problems arise with the increased framework mass, including the high weight of the framework and difficulties with the porcelain-firing cycles. After firing, residual heat in the metal may affect the cooling rate of the ceramic, leading to increased ceramic fracture risk.[13] Recently, it has been claimed that heavier prostheses induce more strain around implants compared with lighter ones.[16] Therefore, a design with increased esthetic material was

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Clinical Implications

Materials with complex geometries can easily be created by direct metal laser sintering. Frameworks can be fabricated with internal parts partially removed so that a significant amount of alloy powder can be saved, lighter frameworks can be fabricated, and fabrication time can be shortened.

recommended for Type 3 IRFPDs to decrease the total weight.[15] This technique may be suitable for metal-acrylic resin prostheses, but restorations with thicker frameworks resist occlusal forces better and have improved fracture resistance. In addition, ceramic veneers greater than 2 mm should be avoided to prevent microcracks within the ceramic.[14] Therefore, designing a thinner framework is not an option for metal-ceramic Type 3 IRFPDs.

Milling is recommended for manufacturing the metal framework for Type 3 IRFPDs.[17] Substituting milled titanium for milled cobalt-chromium (Co-Cr) alloy may be a good solution for decreasing the weight of the framework because of the 55% lower density of titanium.[16] However, the bulk of the framework still jeopardizes ceramic application.[18,19] Moreover, the elastic modulus of an alloy needs to be higher to resist flexure of long-span fixed partial dentures. The elastic modulus of grade 5 titanium alloy (115 GPa) is approximately 2-fold lower than that of the Co-Cr alloy (220 GPa).[20-22] Considering long-span restorations in Type 3 IRFPD, milled Co-Cr alloy is a more convenient material in terms of mechanical properties. However, milling Co-Cr alloy is problematic because of high hardness, which might damage the cutting tools during milling.

The mechanical properties of DMLS Co-Cr alloys have been studied. Choi et al[23] compared the mechanical properties of DMLS with casting and milling and reported 1411 MPa mean tensile strength value for DMLS specimens. Wu et al[24] evaluated the mechanical properties of Co-Cr dental alloy fabricated by DMLS and reported 1307 MPa mean tensile strength. Takaichi et al[25] evaluated the tensile strength of Co-Cr alloys fabricated by DMLS with different laser energy levels and reported mean tensile strength values ranging between 911 MPa and 951 MPa depending on the laser energy levels used. Ucar et al[9] investigated the effect of layered manufacturing techniques, alloy powders, and layer thickness on the mechanical properties of Co-Cr dental alloys and reported 1184 MPa mean tensile strength values. The mean yield strength of DMLS specimens in these studies was much greater than the minimum acceptable values for International Organization for Standardization (ISO) Type 5 materials (500 MPa).[26]

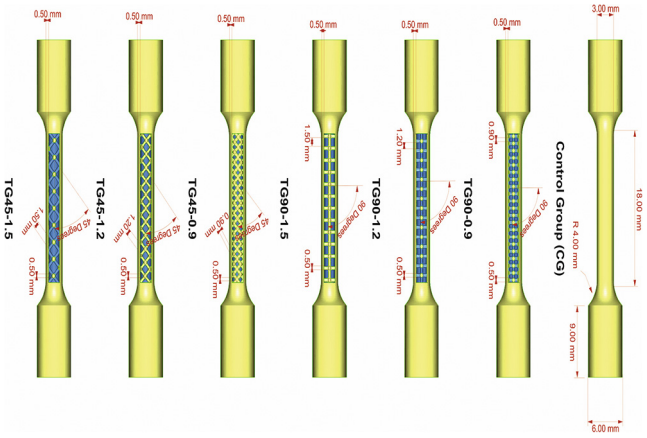


Figure 1. Design of tensile test specimens.

The DMLS technique allows for even complex geometries to be fabricated[3] and is the only technique that allows changing the internal design of the framework. Lattice structures can be fabricated within the closed-hollow geometries. A hollow design enables lighter frameworks to be fabricated with considerably reduced production time, increasing productivity. However, the authors are unaware of a study that has evaluated the effect of internal design changes on the mechanical properties of frameworks fabricated by DMLS.

The aim of this study was to evaluate the effect of internal design changes on the mechanical properties of Co-Cr specimens fabricated with DMLS. The null hypothesis was that changing the internal design would not affect the mechanical properties.

MATERIAL AND METHODS

A power analysis was performed to determine the sample size per group (effect size 0.5, α=.05, power=0.9, number of groups 7, minimum total sample size 67). Dumbbell-shaped tensile test specimens were designed by using a 3-dimensional software program (CAD Solidworks Premium; Dassault Systèmes Solidworks Corp) as per ISO 22674(E). The specimens in the control group were solid. The designs of the specimens in 6 test groups were modified from the control group design. Leaving the outer shell 0.5 mm in thickness and intact in all test groups, changes were made in the internal design (Fig. 1). The columns creating the internal lattice were 0.5 mm in diameter. The design of each test group can be seen in Table 1. A total of 70 tensile specimens were fabricated with DMLS (EOSINT M 270; EOS GmbH) by using a Co-Cr alloy powder with a percent composition of Co 63.9, Cr 24.7, W 5.4, Mo 5.0, and Si 1.0 (Bego Mediloy S Co; Bego GmbH) (n=10). The parameters of the DMLS device are given in Table 2. The specimen supports were cut and ground by the same researcher (O.E.). Before tensile testing, all specimens were weighed

Table 1. Internal lattice design per group

Group*	Inner Bar Angles (degrees)	Distance Between Inner Bars (mm)
CG	-	-
TG90-0.9	90	0.9
TG90-1.2	90	1.2
TG90-1.5	90	1.5
TG45-0.9	45	0.9
TG45-1.2	45	1.2
TG45-1.5	45	1.5

*CG refers to the control group and TG refers to the test groups.

Table 2. Device specifications

Device	Energy Used, W	Scan Speed, m/sec	Production Speed, m^3/sec	Spot Laser Diameter, mm	Layer Thickness, mm
Eosint M270	195	7	20	100-500	20-40

Table 3. ANOVA table

ANOVA	Sum of Squares	df	Mean Square	F	P
Bar weight (mg)					
Between groups	12 81 760.771	6	2 13 626.795	678.591	<.001
Within groups	19 833.000	63	314.810	–	–
Total	13 01 593.771	69	–	–	–
Peak strength (MPa)					
Between groups	13 87 580.343	6	2 31 263.390	104.688	<.001
Within groups	1 39 171.600	63	2209.073	–	–
Total	15 26 751.943	69	–	–	–
Elastic modulus (GPa)					
Between groups	92.763	6	15.461	.919	.487
Within groups	1059.363	63	16.815	–	–
Total	1152.126	69	–	–	–
Elongation (%)					
Between groups	464.000	6	77.333	1.896	.095
Within groups	2569.200	63	40.781	–	–
Total	3033.200	69	–	–	–

individually with an analytical balance (AX120; Shimadzu Corp). A chart was prepared by using a free software program (Research Randomizer, version 4.0) to determine a random testing order.[27] The specimens were subjected to tensile strength test by using a universal testing machine (AT-M500-25 kN; Testometric Co) with a crosshead speed of 1 mm/min until fracture. Tensile strength, elastic modulus, and percentage of elongation values were calculated directly by using the software program (winTest Analysis; Testometric Co). Following tensile testing, one of the fractured test specimens was selected, and the plates at both ends of the dumbbell were cut off. The 2 plates were weighted with the electronic weighing device. The weight of plates was subtracted from the previously weighed test specimens individually. One-way ANOVA followed by the Dunnett T3 test was used for the statistical analysis (α=.05) by using a statistical software program (IBM SPSS Statistics v21.0; IBM Corp).

RESULTS

The ANOVA table (Table 3) showed a statistically significant difference among the groups in terms of bar weight (P<.001) and peak strength (P<.001). However, no difference was observed in terms of elastic modulus (P=.487) or percentage elongation (P=.095). The mean ±standard deviation bar weight, peak strength, elastic modulus, and percentage elongation of the groups are presented in Table 4. No statistically significant difference was found in terms of the mechanical properties between the 45-degree and 90-degree (Table 5) or among the 0.9-mm, 1.2-mm, and 1.5- mm inner bar distances (Table 6). No statistically significant difference was observed between the mean weight of the 45-degree and 90-degree groups (Table 5). However, the mean weight of specimens with 0.9-mm distance was significantly higher than those of the other 2 test groups (bar distance with 1.2 mm and 1.5 mm) (Table 6).

DISCUSSION

In the present study, the effect of internal lattice design on the mechanical properties of the Co-Cr specimens fabricated with DMLS was evaluated. The findings showed that internal lattice design decreased the weight of the specimens and their tensile strength but had no significant effect on the elastic modulus or the percentage elongation. Thus, the null hypothesis was rejected for weight and tensile strength parameters but accepted for elastic modulus and percentage elongation.

Mean peak tensile strength values of DMLS-fabricated Co-Cr specimens have been reported to range between 911 MPa and 1411 MPa depending on the alloy powder and DMLS device.[9,23-25] The mean peak strength of the control group in the present study (1045 ±36.7 MPa) was consistent with that of previous studies.[9,23-25] As expected, a decrease in the mean peak tensile strength compared with the control group was observed because of the removal of material to create the internal lattice design. However, alterations to the inner bar angles and increasing distances between the inner bars did not change the peak tensile strength values significantly.

When calculating the strength and the elastic modulus, a solid cross-section area was used for all groups. Although, the presented results were calculated in a way disadvantageous to the test groups, the results were higher than the required minimum ISO values.[26] The mechanical properties of the test groups would have been even higher than the presented results if the true cross-section area had been used. This should be taken into consideration when evaluating the results.

Table 4. Respective mean ±standard deviation values of specimens

Group	Bar Weight (mg)	Peak Strength (MPa)	Elastic Modulus (GPa)	Elongation (%)
CG	1321.3 ±36.6^{A*}	1045 ±36.7^{A}	284.2 ±71.9^{A}	28.7 ±7^{A}
TG45-0.9	1086.9 ±8.5^{B}	674.8 ±56.9^{B}	188.4 ±70.9^{A}	24.1 ±5.8^{A}
TG45-1.2	946.0 ±10.1^{D}	645.5 ±16.8^{B}	192.6 ±39.1^{A}	22.7 ±6.2^{A}
TG45-1.5	909.1 ±10.3^{E}	616.5 ±58.1^{B}	190.4 ±66.9^{A}	23.2 ±5.6^{A}
TG90-0.9	1013.7 ±17.9^{C}	656.8 ±71.1^{B}	180.3 ±70.5^{A}	19.8 ±4.4^{A}
TG90-1.2	944.9 ±10.2^{D}	656.5 ±27.3^{B}	184.7 ±48.6^{A}	25.0 ±7.0^{A}
TG90-1.5	922.7 ±12.2^{E}	626.1 ±37.3^{B}	170.3 ±67.0^{A}	25.9 ±7.8^{A}

*Different uppercase letters indicate statistically significant differences ($P \leq .05$).

Table 5. Comparison of bar weight and mechanical properties between different bar angles

Evaluated Parameter	*P*	F Value	Degree of Freedom	*P* 45 vs 90 Degrees
Bar weight	<.001	147.466	2	.518
Peak strength	<.001	281.462	2	.997
Elastic modulus	.063	2.886	2	.828
Percentage elongation	.065	118.533	2	.989

Table 6. Comparison of bar weight and mechanical properties between different bar distances

Evaluated Parameter	*P*	F Value	Df	*P* (0.9mm-1.2mm)	*P* (0.9mm-1.5mm)	*P* (1.2mm-1.5mm)
Bar weight	<.001	491.662	3	<.001	<.001	.763
Peak strength	<.001	214.777	3	.9	.095	.102
Elastic modulus	.145	1.861	3	1.000	1.000	.996
Percentage elongation	.068	2.492	3	.786	.579	.986

The elastic modulus of the framework is important for the clinical success of metal-ceramic restorations. The higher the elastic modulus, the higher the resistance to deformation of a given alloy.[9] Although brittle ceramic materials may fracture when the resistance of the metal framework to deformation is high, ceramic can withstand mastication forces without fracture, and the marginal integrity can be maintained. The results of the present study demonstrated that the elastic modulus of the frameworks can be maintained even with a modified internal design. The peak tensile strength, elastic modulus, and percentage elongation of all groups in the present study satisfied the criteria for Type 5 alloys in ISO 22674(E) (tensile strength: >500 MPa, percentage elongation: >2%, elastic modulus: >150 GPa).[26] Although a statistically significant difference was found among the test groups and the control group for the tensile strength, the difference was not clinically significant because all tested groups were greater than the minimum strength specified by the ISO standard. Thus, the frameworks with changed lattice designs can be used for the construction of long-span metal-ceramic restorations.

Changing the internal design of the laser-sintered specimens affects the amount of the powder used, the time to manufacture the specimen, and the weight of the specimen. The present study aimed to show that the weight of the specimens will decrease if the internal design is changed. The midsection of a dumbbell-shaped specimen is projected to the applied forces during a tensile test, while the ends of the specimen are fixed to the crossheads of the universal testing machine. Therefore, the ends of the specimen were solid, and no internal design changes were made to the ends of the tensile specimen. If the total weight of the specimens had been compared, the weight change due to the internal design change would have been underestimated. Nevertheless, cutting the 2 solid ends of the specimens was necessary. For standardization, the 2 ends of only 1 specimen were cut and subtracted from the weight of each specimen. By doing so, the human error when sectioning the specimens was minimized.

The results of the present study have clinical implications. First, the internal lattice design increases the productivity of DMLS. The time needed for fabricating a framework with DMLS is proportional to the sum of the cross-sectional area of layers to be laser scanned.[3] Therefore, the production time can be decreased considerably by changing the internal design. Another advantage is that by changing the internal design, a significant amount of alloy powder can be saved, and lighter restorations can be fabricated. Thus, strain generated around implants under the effect of gravity can be decreased because of a lighter framework.[16] In the present study, the optimal design in terms of productivity and weight was the 1.5-mm internal lattice design (either perpendicular or cross-sectional), which did not compromise the mechanical properties. However, it should be stressed that the lowest mean values for mechanical properties were observed for this group.

Limitations of the study included that the actual production time per specimen could not be calculated individually. All test specimens were fabricated on a 25×25-cm build plate at the same time because of the working regulations of the dental laboratory. Therefore, statistical data cannot be presented regarding the production time. Future research should evaluate the effect of ceramic application on the marginal and internal accuracy of the frameworks with the changed internal design.

CONCLUSIONS

Based on the findings of this in vitro study the following conclusions were drawn:

1. Co-Cr dental frameworks fabricated with DMLS conform to the criteria for Type 5 in ISO 22674(E).
2. When the internal design of the tensile test specimens was changed, the mechanical properties still met the minimum criteria established for Type 5 in ISO 22674(E).
3. The weight was reduced significantly with the hollow design.

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Acknowledgments
The authors thank Özel Adana Çağdaş Dental lab for provision of alloy powder and fabricating test specimens, especially Mr. Remzi Zeytinli for his limitless efforts in designing test specimens.

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https://doi.org/10.1016/j.prosdent.2021.06.018