The Saudi Dental Journal 36 (2024) 296–300

Contents lists available at ScienceDirect

The Saudi Dental Journal

journal homepage: www.ksu.edu.sa
www.sciencedirect.com

The effect of repeated baking of porcelain on its bonding strength to a Co-Cr alloy 3D-printed by selective laser melting

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ARTICLE INFO

Keywords:
Repeated porcelain baking
Cobalt-Chromium (Co-Cr) alloy
Selective Laser Melting (SLM)

ABSTRACT

Objectives: This study aimed to evaluate the effect of multiple baking cycles of porcelain on its shear bond strength to a cobalt-chromium (Co-Cr) alloy that is three-dimensionally printed using Selective Laser Melting (SLM) technique.
Materials and methods: The research sample comprised forty-eight discs measuring 5 mm × 3 mm, divided into four groups according to: the manufacturing method (SLM, casting) and the number of porcelain baking cycles (1, 3) as follows: Group A: Co-Cr alloy by SLM with one baking cycle; Group B: Co-Cr alloy by SLM with three baking cycles; Group C: Ni-Cr alloy by casting with one baking cycle; Group D: Ni-Cr alloy by casting with three baking cycles. Then, porcelain was melted on disks, shear testing was performed and the values of the Shear Bond Strength (SBS) in MegaPascals (MPa) were calculated.
Results: The mean SBS values for each group were (A: 25.69 - B: 19.51 - C: 35.72 - D: 28.67 MPa). Statistical analysis showed that the manufacturing method and the number of porcelain baking cycles had a significant influence on shear bond durability ($P > 0.05$): the strength of this bond decreased when baking cycles increased. The Co-Cr samples manufactured by SLM also showed a decrease in binding strength compared to the Ni-Cr samples made by casting.
Conclusion: Repeated baking of porcelain reduces the strength of the porcelain bond with the Co-Cr alloy made by Selective Laser Melting (SLM) technique.

1. Introduction

Computer Aided Design and Manufacturing (CAD-CAM) technologies have become widely used in dentistry in various fields, especially in prosthetic dentistry, because of its ease of use, speed and accuracy of manufacturing (Alghazzawi, 2016). Moreover, it was used to fabricate prosthetic metal structures as an alternative to the traditional casting method. This technique is based on mechanical removal of a block to obtain the required prosthetic component; however, the use of this method in making prostheses became limited due to the rapid wear of the burs used, the constant need for maintenance, its high cost, and the waste of materials (Yang and Li, 2022).

The manufacturing technology of addition or construction (Additive Manufacturing AM) which includes material extrusion, sheet lamination, material jetting, and direct energy deposition (Chua et al., 2023) appeared as a replacement of the method of removal (Subtractive Manufacturing SM) that includes milling, laser cutting, and water jet cutting (Yang et al., 2021). For instance, three-dimensional (3D) printing is an SM techniques that is used to make various metal prosthetic parts such as fixed prosthetic components, implants prosthesis and structural removable prosthesis (Rutkūnas et al., 2022), by building and merging layers of metal powder layer by layer (20–40 mm) through a beam of high-concentration laser beams (selective laser melting SLM), after importing prosthetic design data from the computer (Kaleli et al., 2020). One important feature of this method is decreased waste of materials and manufacturing time compared to the subtractive method. The

Abbreviations: SLM, Selective Laser Melting; MPa, Megapascals; Co-Cr, Cobalt-Chromium; Ni-Cr, Nickle-Chromium; SBS, Shear Bond Strength; CTE, Coefficient of Thermal Expansion.

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https://doi.org/10.1016/j.sdentj.2023.11.002
Received 21 July 2023; Received in revised form 31 October 2023; Accepted 1 November 2023
Available online 2 November 2023
1013-9052/

metal mixture used in this technique is often cobalt chrome Co-Cr (Viderščak et al., 2021) (See Figs. 1–3).

Metal-ceramic prostheses have been widely used in dentistry since they combine both the cosmetic aspects of the porcelain and the durability and strength of the metal; thus they provide a similar appearance of natural teeth as well as good mechanical properties on the other (Sailer et al. 2018; Pjetursson et al., 2015).

Nickel chrome (Ni-Cr) alloy is casted using lost wax technique, which is considered the most common mixture in the manufacture of metal-ceramic prosthesis because of its cheap price, ease of casting and good bonding durability (Kaleli et al., 2020), given the importance of this property for the success of these compensators (Pjetursson et al., 2015). This bonding is both physical (Vandervalls forces), and chemical, but the latter is more dominant (Bahri et al., 2020).

On the other hand, to meet aesthetic and clinical requirements, metal-ceramic crowns must undergo an indispensable set of porcelain baking cycles. There may be additional baking cycles caused by possible morphological or shade modifications; however, these cycles could affect the strength of the metal-ceramic bond (Anwar et al., 2015).

There have been many studies on the technology of making metal through the 3D printing method using SLM in terms of the physical and chemical properties of the resulting metal prosthesis (Fu et al., 2022). However, studies on the strength of the ceramic–metal bond were very few and contradictory.

A study by Di Fiore et al. found that bonding values were within the acceptable values of 80 % (Di Fiore et al., 2020); on the other hand, Revilla-León study found no difference in the ceramic bonding values of the cobalt-chromium alloy between the additive and subtractive methods (Revilla-León et al., 2022).

Hence, this study aimed to assess the effect of repeated baking of porcelain on the durability of its shear bonding strength with cobalt-chromium alloy that is 3D-printed using Selective Laser Melting (SLM).

2. Materials and methods

The study sample comprised 48 metal discs measuring (5 × 3 mm), divided into two main groups according to: firstly, the method of manufacture (SLM using Co-Cr alloy, or the Conventional casting using Ni-Cr alloy); secondly, the number of porcelain baking cycles (one cycle, or three cycles) as follows: [Table 1].

Group A: 12 discs of Co-Cr alloy by SLM with one baking cycle.
Group B: 12 discs of Co-Cr alloy by SLM with three baking cycles.
Group C: 12 discs of Ni-Cr alloy by casting with one baking cycle.
Group D: 12 discs of Ni-Cr alloy by casting with three baking cycles.

24 metal discs were cast from a Ni-Cr alloy (Phase-N, France) using the lost wax method, and 24 metal discs fabricated by 3D-printing using (SLM) method from a Co-Cr alloy powder (Realloy-C, Germany) using a device (Mysint100-sisma, Italy).

All discs were sandblasted by Aluminum Oxide Al2O3 granules measuring 250 μm and a pressure of 4 bars, after which the porcelain baking process was completed according to the following stages:

Application of (OPAC) porcelain.
Application of dentine porcelain followed by the enamel porcelain, then finalized with glazing.

Fig. 2. Placing disc in an acrylic block for ease of use during shear stress measurement.

Twelve discs from each group were subjected to three additional baking cycles and then all the discs were placed in acrylic bases which are easy to use during the application of the shear stress test.

Shear forces (SF) necessary for separating porcelain from metal base were measured using the mechanical Tester (Testometric) whose head speed was 1 mm per minute.

Forces (F) were recorded in Newton and then divided by the Surface Area (SA) to obtain the Shear stress (S) in Megapascals (MPa) by the following equation: $S = F/SA$

3. Results

The shear stress necessary for the occurrence of bonding failure between metal and porcelain was calculated in MPa for each of the four study groups, and then the effect of the different metal fabrication methods and the number of porcelain baking cycles on the shear stress necessary for the occurrence of failure were studied.

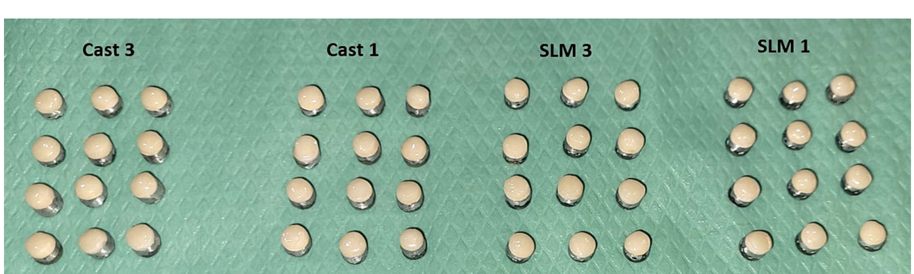

Fig. 1. Shows four groups of metal alloy Shows four groups of discs following porcelain application divided according to the baking cycles (Cast 1, Cast 2, SLM 1, SLM 2).

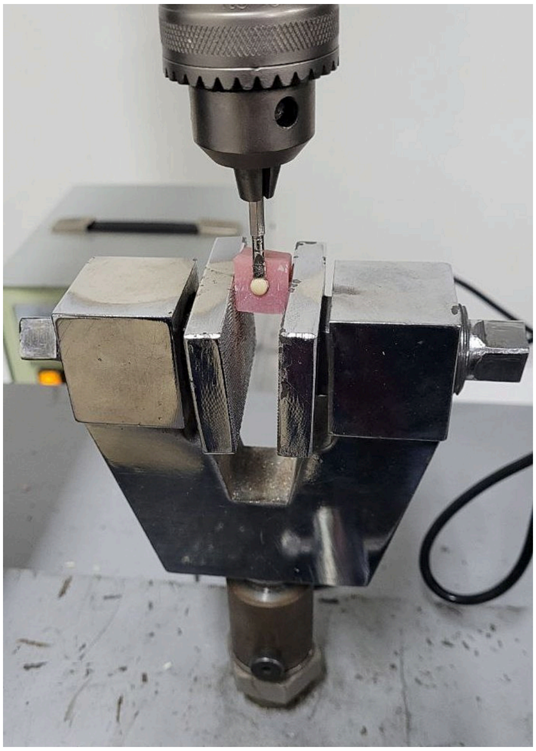

Fig. 3. Shows shear stress measurement device used in this study.

Table 1
Distribution of study sample according to the fabrication method and number of baking cycles.

Manufacturing method	Number of baking cycles	Number of discs	Percentage %
Selective Laser Melting (SLM)	One	12	25
	Three	12	25
Cast	One	12	25
	Three	12	25

3.1. *Descriptive statistical study*

The mean values of shear stresses necessary for the occurrence of failure between metal and porcelain were calculated for each of the research groups and then other statistical variables were calculated and organized in [Table 2] and illustrated in [Diagram 1].

3.1.1. *Statistical-analytical study of the effect of the number of ceramic baking cycles on shear stresses between metal and porcelain according to the method of making the metal*

After confirming the normal distribution of data using Shapiro-Wilk test ($P > 0.05$); data was analyzed using computer statistical package SPSS (Version 24); T-student test for independent samples was performed to examine the effect of the number of porcelain baking cycles on the shear stresses necessary for the occurrence of failure between metal and porcelain according to the method of making the metal as follows;

T-Student test results for independent samples:

The significance level value is much smaller than 0.05, and this means that at the 95 % confidence level, there were statistically significant differences in the average shear stresses necessary for failure to occur between metal and porcelain, no matter how the metal is fabricated.

It is also noted that the significance level value is smaller than 0.05 when comparing the average shear stresses between metal and porcelain, regardless of the method of making the metal. By studying the algebraic indication of the differences between the means, we conclude that the values of shear stresses when baking porcelain one time were greater than those when baking porcelain three times.

3.1.2. *Statistical-analytical study of the influence of the method of making metal on the shear stresses between metal and porcelain according to the number of porcelain baking cycles*

After confirming the normal distribution of the data using the Shapiro-Wilk test ($P > 0.05$); a T-student test of independent samples was performed to study the effect of the metal fabrication method on the shear stresses necessary for the occurrence of failures between metal and porcelain according to the number of porcelain baking cycles as follows;

T-Student test results for independent samples:

The significance level value is much smaller than 0.05, and this means that at the 95 % confidence level, there were statistically significant differences in the average shear stresses between metal and porcelain; regardless of the number of porcelain baking times.

It was also noted that the significance level value is smaller than 0.05 when comparing the average shear stresses necessary for the occurrence of failure between metal and porcelain, regardless of the number of ceramic baking cycles. By studying the algebraic signal of the differences between the averages, we conclude that the values of shear stresses when making metal by SLM method were lower than their counterparts when making it using conventional casting method.

4. Discussion

The durability of the bond between porcelain and metal is an important factor for the success of metal-ceramic prostheses (Pjetursson et al., 2015). Shear test was applied as the best indicator in assessing binding strength since it focuses on the interface of the material until complete separation occurs.

Advances in dental technology over the past decades have led to the creation of alternative methods that substitute the need for using casting method in fabricating prostheses. These new technologies included 3D printing using SLM, which surpassed many advantages (Viderščak et al., 2021). However, it was necessary to assess the correlation of porcelain with these metal mixtures used with SLM technology. Ni-Cr alloy using casting method was chosen as the most commonly used method for fabricating fixed prosthesis given its low cost, strength and its good correlation with overlaying porcelain (Chen et al., 2014). Also, Co-Cr alloy powder was used in this study because it is the most commonly used alloy when applying SLM technology, whereas the Ni-Cr alloy is rarely used with this method due to the possibility of being cracked and the porous structure in the prosthesis made under this method (Ghoussoub et al., 2022).

Studies have reported that casting Cr-Co alloys is more difficult than casting Ni-Cr alloys and that the bond between porcelains and these alloys is often found to be weak due to the fact that its Coefficient of

Table 2
A table shows mean values, standard deviation values, and minimum and maximum shear stress values in MPa.

Studied Variable	Manufacturing method	Baking cycles	Discs	Mean	Standard Deviation	Miuimum	Maximum	Shapiro-Wilk p
Shearing Stress (MPa)	SLM	1	12	25.69	0.98	23.71	27.08	0.524
		3	12	19.51	1.01	17.92	20.91	0.445
	Cast	1	12	35.72	1.24	33.49	37.72	0.907
		3	12	28.67	1.29	26.23	30.06	0.154

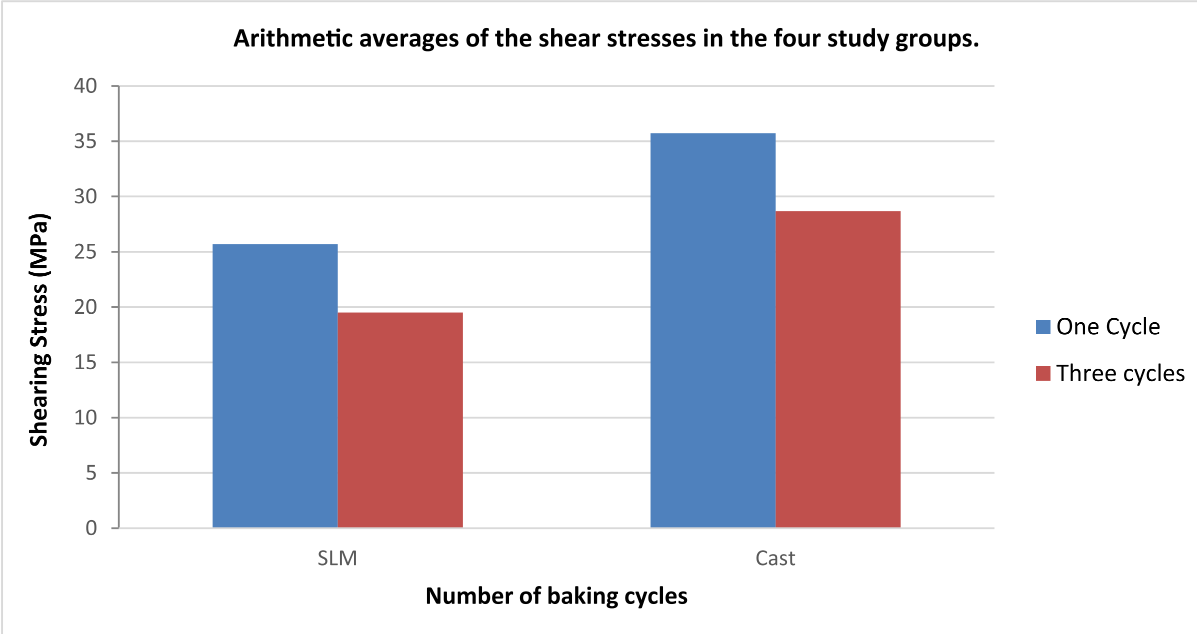

Diagram 1. A diagram shows mean values of shear stresses for all studied groups.

Thermal Expansion (CTE) is incompatible with porcelains; however, the strength of this bond also depends on other physical, mechanical and chemical factors (Han et al., 2018).

The results of this study indicate that the durability of the bond of porcelain with metal for both the casting and SLM printing methods during single baking cycle of porcelain is acceptable (Ni-Cr:35.72-Co-Cr:25.69 MPa) based on the standards of the World Organization of Metrology (ISO 9693: 2012) for the evaluation of the metal-ceramic bond, where the acceptable bond values were set at 25 MPa (ISO 9693-1:2012). However, the bond was stronger with Ni-Cr alloy in the casting method, and this may be due to the formation of the oxide layer suitable for bonding porcelains during the traditional warm up and casting procedures; while in the SLM technique, the fabrication is made within an inert gas environment (Argon-Nitrogen) and then heat treatment is carried out to compensate for the internal stresses resulting from laser fusion of layers during fabrication process, at which, the oxide layer necessary for bonding ceramics may be generated. However, this layer is heterogeneous and unsuitable leading to a weaker bond (Pagnano et al., 2021).

Moreover, Ko et al. found that SLM is considered to be a superior manufacturing method to casting if appropriate heat treatment is included. Most of the residual stress, except for the micro residual stress, was reduced during heat treatment at 750 °C (Ko et al., 2022).

Repeated baking of porcelain for three cycles had a negative effect on the shear stress values for both methods (Ni-Cr:28.67-Co-Cr:19.51 MPa), and this decrease in binding strength may be attributed to the increased thickness of the layer of oxides formed at the metal-porcelain interface (Ekren et al., 2018).

The correlation values in the Ni-Cr casting group when the porcelain was baked for 3 cycles was (28.67 MPa) which is higher than the previously specified value within ISO and this is clinically acceptable.

While the correlation values in the SLM printing group using Co-Cr when repeated baking of porcelain was (19.51 MPa) which is lower than the acceptable values and lower than the values of the casting group, this may be due to the thickness of the oxide layer formed from repeated baking and the lack of compatibility rate between the CTE of metal and porcelain. When the difference is greater than 1×10^{-6}K, this leads to increased stresses across the interface, which in turn leads to weak binding strength (Hong et al., 2020), as Ucar pointed out that increasing the number of refractoriness leads to a decrease in the rate of thermal compatibility between porcelain and metal and as a result leads to a decrease in the strength of the metal-porcelain bond (Ucar et al., 2009).

In comparison with the results of the previous study, Bahri's study showed that there was no difference in the binding values between ceramics and both Co-Cr and Ni-Cr alloys manufactured by conventional casting (Bahri et al., 2020); however, Di Fiore found upon studying the effect of 3D printing of a Co-Cr mixture on the strength of the metal-porcelain bond that 80 % of the binding values was within the acceptable rangewhile 20 % was under 25MPA. This corresponds to the result of our study (Di Fiore et al., 2020).

In the study of Farzin, they found that baking porcelain whether by the casting method for Ni-Cr mixture or carving for cobalt-chromium mixture for one cycle and 3 cycles didn't affect the binding values, and these values are higher in Co-Cr than Ni-Cr. We attribute the difference in the results between the two studies to the different method of making Co-Cr metal (Farzin et al., 2018).

The study of Ren did not observe any effect of repeated baking of porcelain on the bond strength of Co-Cr alloy fabricated by both SLM and casting; however, it was larger in the SLM group. This is different from the results of our study, probably due to the difference in the metal type used by the casting method (Ren et al., 2016).

Ashtiani also found that the effect of repeated baking of porcelain (one cycle, three cycles) on the bond strength with a Co-Cr alloy manufactured by the carving method didn't affect the bond, and this may be due to the difference in the method of manufacture (Ashtiani et al., 2021).

Finally, in a study by Revilla, et al. to evaluate the correlation of ceramics with Co-Cr alloy manufactured by different methods (casting, carving and printing), there was no difference in the correlation values between the manufacturing methods.

5. Conclusion

Within the limits of this study, we conclude the following:

- The bond durability between porcelain and cobalt chrome Co-Cr alloys made by the SLM 3D printing method is acceptable within the standards of ISO 9693: 2012.
- The baking of porcelain for three more cycles had an impact on the strength of the bond and was below the acceptable values within the standards of ISO 9693: 2012.
- The bonding of porcelain with nickel–chromium Ni-Cr alloys is good and suitable even if the porcelain baking is repeated for three more cycles.

Thus, we recommend avoiding repeated baking of porcelain with additional cycles if the metal structure is made by printing method, because this affects the durability of the metal-porcelain bond.

Place of research

The research was conducted at the department of restorative dentistry, Arab University of Science and Technology (AUST), Hama Homs international road, Tel Qartal Junction, Syria.

Ethical statement

This work has been approved by the appropriate **ethical** committees related to the institution (Damascus and Tishreen University).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

I thank the committee of Arab University of Science and Technology (AUST) for their moral support and facilities they provided.

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