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Scientific Facts

Zirconia-supported Ceramic Restorations: Uncovering the Mysteries

Comments from focus groups, lectures, research studies, and magazine articles over the past year have prompted debate among dentist and dental laboratory professionals over the viability of zirconia supported restorations¹. For a few dental laboratories and dentists it has been a source of aggravation and for the vast majority, zirconia-supported restorations have been extremely successful.

In one round table conference², the following two comments were expressed about zirconia-supported restorations:

"I am concerned with porcelain chipping off my zirconia restorations... as this can cause frustration in removing and replacing."

"I have been regularly placing zirconia restorations for four years now, and have not had to replace a single restoration due to chipping."

So, which is right? The likelihood is that both are accurate statements and both situations exist. Chipping is not new to our industry. It occurs in natural enamel, porcelain fused to metal (PFM) crowns, porcelain fused to alumina, pressed ceramics, and of course, all-porcelain crowns. However, there are properties unique to zirconia, that when better understood, can help increase the predictability and longevity of successful zirconia-based restorations. The information in this document is intended to:

1. **Develop a better understanding of zirconia materials** and the properties that differ from conventional precious and semi-precious metal alloys.
2. **Describe factors that can impact the durability** of porcelain over zirconia and how these factors can be minimized.

Understanding Transfer of Heat³

Material	Young's Modulus (GPa)	Melting Point (°C)	Thermal Conductivity W/(mK)
Silver ³	83	962	429
Gold ³	78	1064	318
Gold Alloy ⁴	93	1100	200
Base Metal ^{4,5}	204	1240	40
Alumina ^{4,6}	360	2072	30
Zirconia ^{4,7}	200	2700	2

The table above displays several materials that are commonly used in the fabrication of dental restorations. The first four metal materials are often used in some combination to create alloy frameworks for porcelain restorations. There are distinct differences between zirconia and the other materials listed.

The data above is presented to draw general conclusions pertaining to fabrication of zirconia supported porcelain restorations and PFM restorations and heat transfer through the materials. Thermal conductivity is a material's ability to transfer heat through a unit thickness due to a temperature gradient. As a generalization, compared to the other materials, zirconia has the:

- greatest stiffness.
- highest melting point.
- lowest thermal conductivity.

Consequently, zirconia requires a significantly longer duration for heat to be transferred within the material in order to reach a uniform temperature throughout the material.

In Summary: Zirconia conducts heat at a slower rate than common dental alloys.

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1 CR Report, October and November 2008, DLP Editorial "Clearing Confusion" October 2008, Journal of Dental Technology, "A block's a block's a block", August/September 2008.
2 3M ESPE Council of Innovative Dentistry, September 2008.
3 Periodic Table at ChemicalElements.com for Young's Modulus, Melting Point and Thermal Conductivity
4 Swain MV, "Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures", Acta Biomater (2009), doi:10.1016/j.actbio.2008.12.016 for Young's Modulus and Thermal Conductivity.

5 Argen Corporation, Dental Alloys for Melting Point (Gold Alloy: Argendent 75, Base Metal: Argeloy NP).
6 Inchem.org for Melting Point of Alumina (Aluminum Oxide).
7 3M Internal Data for Melting Point.

Heating and Cooling Overlay Porcelain

Thermal conductivity of the zirconia is a very important consideration when firing porcelain on zirconia copings or bridge frameworks. If it requires significantly more time for heat to transfer through the zirconia and to attain proper temperatures of the porcelain adjacent to the coping or bridge framework, then we would naturally assume that respecting the heat rise given for a porcelain and not taking short-cuts here as well as the overall firing duration will allow the materials the proper time to reach the appropriate temperatures and attain the desired porcelain vitrification.

As we consider slower heat dissipation from the zirconia coping or framework, another important consideration is the impact this will have on the overlay porcelain or the porcelain/zirconia interface during our cooling cycle. Since it requires significantly more time for heat to dissipate from the zirconia, the overlay porcelain will cool at a dramatically different rate than the zirconia, which will impact the desired compression of the overlay porcelain.

If we lower the pedestal on the furnace quickly, the outer porcelain will cool quickly while the porcelain closer to the zirconia will cool more slowly. It is likely this non-uniform cooling of the porcelain will create differential stresses within the porcelain which can potentially lead to porcelain chipping. Therefore, we would conclude that slowing our cooling rate will also help allow for more favorable temperature distribution across the material.

In Summary: Glass ceramic material over zirconia requires slower heating and cooling rates than ceramic material over traditional dental alloys.

Coefficient of Thermal Expansion (CTE) of Zirconia and Porcelain Materials

Coefficient of Thermal Expansion is described as the fractional change in length, or volume, of a material for a unit change in temperature. Zirconia copings generally have a CTE of $10.2 \cdot 10^{-6} \text{ K}^{-1}$ to $10.8 \cdot 10^{-6} \text{ K}^{-1}$ and the specific CTE is impacted by the specific chemical composition of the supplier. A variety of overlay porcelains are available and these can have CTEs ranging from roughly $7 \cdot 10^{-6} \text{ K}^{-1}$ to $15 \cdot 10^{-6} \text{ K}^{-1}$.

In PFM restorations, it is generally preferred to have the CTE of the porcelain slightly lower than that of the metal substrate to ensure cooling during compression (porcelain enamel is much stronger in compression than tension).

Specific porcelains are designed for zirconia copings and of course, those porcelain materials with a CTE closest to that of the specific zirconia are generally considered ideal. But, even with compatible CTE values, cooling too rapidly, coupled with varying thicknesses of the zirconia coping, may create undesirable temperature gradients within the porcelain during the cooling process. Should this occur, there is potential for internal thermal differential stresses within the overlay porcelain that may result in fracture and chipping issues.

“Many technicians still have a ‘PFM mentality’. With PFM, lab technicians found multiple temperature and heat rate formula options to achieve the right end state. However, labs can’t think that way with zirconia, because of the heat conductivity. We need to stick to the fundamentals of firing in layers, and not take shortcuts with heat and cool rates”

— Robert Wisler, CDT, Alpha Dental Studios

In Summary: To maintain greater control of uniform temperature of the porcelain, slow the cooling process.

A Simple Experiment

This simple experiment⁸ was conducted to illustrate the impact of porcelain processing pertaining to zirconia substructures. Equal amounts of unfired clear porcelain, designed for zirconia copings (fig. 1), are shown with an unsupported specimen on the left and a sintered zirconia substrate on the right. These specimens were processed together with the same heat rise, hold and cooling protocol, and results are shown in figs 2–5. Fig. 6 shows the ceramic after a slower heat rise during firing and extended cooling process. Because the zirconia substructure is able to attain proper heat throughout and transfer the heat, we see a properly vitrified porcelain/zirconia interface.

⁸ Johnson, Ryan E. “Veneering Ceramic Failures on Zirconia Restorations”, Lab Day Chicago, February 2009.



fig. 1 Unfired clear porcelain powder (left), unfired clear porcelain on 3mm zirconia substrate (right).



fig. 2 Samples after firing and cooling.



fig. 3 Underside of fired surfaces. Note non-vitrified area on sample (right) from zirconia substrate.



fig. 4 and fig. 5 Enlargements of fig. 3 showing clear porcelain fully vitrified (left) and non-vitrified or under-processed (right).



fig. 6 New sample of clear porcelain powder on 3mm zirconia substructure after heating and cooling. Sample is fully vitrified. A slower heat rise and extended cooling process was used.

Source: 3M ESPE internal data

Zirconia Coping or Bridge Framework Design and Overlay Porcelain Thickness

An important consideration for designing a coping or bridge framework is that it provides proper support for the overlay porcelain and a uniform thickness of overlay porcelain. The danger of not providing adequate support for the porcelain is obvious as it presents the possibility for porcelain fracture. This holds true even for traditional PFM restorations.

“Dentists must ensure that their lab technicians are taking care to properly design zirconia and PFM frameworks. The frameworks should have a miniature crown anatomy.”

—Dr. Gordon J. Christensen

Advanced software tools are now available to laboratories to make it easier to properly design frameworks.



Left (poor design): This cross section shows the zirconia framework is not providing proper support for the porcelain.

Right (proper design): This cross section shows a zirconia coping “miniature crown anatomy” which provides adequate proper support for the overlay porcelain.

Samples and photos by:
Dr. Gordon J. Christensen, D.D.S., M.S. D, PhD., ScD., D. Ed&Res.

In addition, if a zirconia coping is not designed to allow a uniform porcelain thickness, this could contribute to poor overall vitrification of the overlay porcelain. The non-uniform porcelain thicknesses would heat at different rates which could lead to thicker porcelain areas not being fully processed. This effect would be more pronounced when faster heat rises are programmed. Again, this further strengthens our consideration to respect the heat rise and protocols of the overall duration of the process instead of taking “shortcuts”.

“Support of the veneering ceramic against the load in the oral environment is key to the longevity of the restoration. If we step on a 1/4” sheet of glass that is on the carpet it will break immediately. However, if that same sheet of glass is on top of a table at a furniture store or restaurant we can step on it without breaking. The same principle applies with dental restorations. The ceramic must be supported by metal, alumina, zirconia, or tooth (ideally enamel). Much success has been reported with metal and zirconia when properly designed.”

—Dennis Ouye, CDT

In Summary: For optimal success, it is critical that the design of the coping or substructure provides proper support for the overlay porcelain and a uniform thickness of overlay porcelain. This is true for PFM and zirconia.

Furnace Calibration and Thermal Loading

As zirconia copings and bridge frameworks have such a lower thermal conductivity than metal, it is important to ensure furnaces are calibrated on a regular basis for proper porcelain vitrification. Even the same furnace model and brand may have differences in the overall firing cycle. In addition to the analog or digital displays of the furnace, regular testing by firing clear porcelain provides a visual display of vitrified porcelain and added assurance of proper heat and cooling cycles.

When firing porcelain on multiple zirconia copings or bridge frameworks, the overall thermal load is important. Just as it would require more time to bring three or four potatoes to a properly baked condition in an oven than it would take for just one potato, multiple zirconia restorations would take longer to reach proper vitrification than just one zirconia restoration.

In Summary: With zirconia restorations, it is even more important to ensure that furnaces are properly calibrated. Since thermal loading affects the actual heat and cool rates achieved, this must also be considered.

Surface Preparation and Sandblasting

Most computer-aided designs of zirconia copings are done with high precision to define the interior and exterior surfaces and eliminate additional finishing or sandblasting of these surfaces. In contrast to metal copings, where finishing is required prior to processing overlay porcelain, zirconia copings do not need cleaning or surface preparation with rotary instrumentation. Sandblasting the outer surface of a Lava™ Zirconia coping is not necessary as the milling process results in an adequately rough surface to accept the overlay porcelain. However, very light sandblasting does not appear to have affected strength and appears to increase wetting of the porcelain.

Typically, once the zirconia coping is milled, rotary instrumentation is used to separate it from the sprues of the frame holder. It is unavoidable to do some finishing at the sprue site. However, this should be minimal. After this minimal finishing, it is best to perform limited sandblasting of just that area with < 50 µm sand material at a maximum blast pressure 1-1/2 to 2 bar.

In Summary: Other than light sandblasting of the area separated by burs, sandblasting the outer surface of the zirconia coping is not necessary.

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Wash Firing

Wash firing, applying a slurry coat or bonding layer is considered unnecessary with Lava zirconia copings when Lava™ Ceram Porcelain is used. When other products are used, laboratory technicians may apply a thin wash of dentin porcelain to ensure the porcelain vitrification or enhance the mechanical adhesion between the zirconia coping and overlay porcelain. Laboratory

technicians often fire this very thin layer 15–20°C higher than normal porcelain firing specifications. Some have recommended a higher firing of this layer at 50–80°C higher than specifications.

In Summary: Although some lab technicians may apply a thin wash of porcelain to enhance mechanical adhesion between zirconia and overlay porcelain, this step is considered unnecessary when Lava Zirconia is used with Lava Ceram porcelain.

General Suggestions for Processing of Porcelain for Zirconia from Dr. Ed McLaren

With a better understanding of the various factors impacting fabrication of zirconia supported porcelain restorations, the following is a protocol provided by Dr. Ed McLaren, Director of the UCLA Center for Esthetic Dentistry and UCLA School for Esthetic Dental Design:

1. Ensure proper design of coping framework to support overlay porcelain.
2. Once pre-sintered coping or bridge framework is removed from zirconia block, carefully finish sprue attachment sites.
3. Once coping or framework is sintered and if any grinding is necessary, use a new fine diamond (e.g. Brasseler #8881) under copious amounts of water. Gently sandblast any ground areas using 50 µm sand at 25 psi.
4. Apply a thin layer of dentin wash porcelain and fire to a minimum of 50°C higher than manufacturer's firing recommendation (temperature will vary with manufacturer, the key is to attain a glassy appearance on this layer).
5. Build porcelain.
6. **Fire porcelain at a slow heat rise of 30°C per minute on each bake.** As each oven is different, ensure that the oven is calibrated regularly to attain a visual of properly fired porcelain.
7. Hold for one minute.
8. **Slow cool the final bake (i.e. the glaze bake) for six minutes, cooling at 60°C per minute.**
9. Leave on the muffle until the temperature reads under 100°C. This will take ten minutes. Thus the total slow cool cycle on the last bake will take approximately 15 minutes.

The preliminary results using this protocol have been very favorable for Dr. McLaren and are summarized in the following chart. Based on these initial favorable findings, Shane White, DDS, UCLA School of Dentistry, Director of Materials Research is designing and developing further research tests to evaluate and assess the effectiveness of this protocol.

Failure Loads — Porcelain to Zirconia Substrates

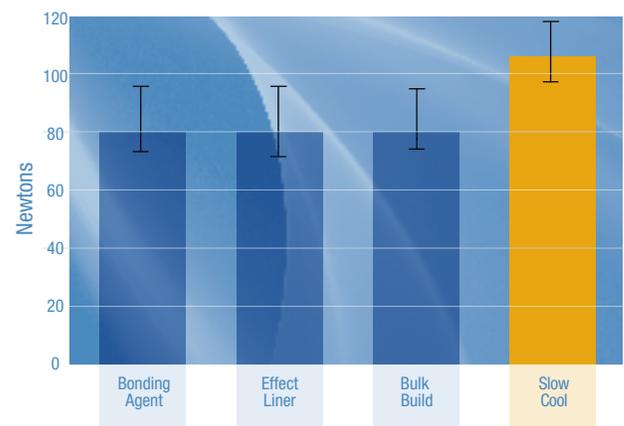


fig. 7 4-point bend test with hand-layered porcelains with sintered zirconia substrates. Four different process modifications are shown. The first three modifications showed little effect on fracture strength, whereas the fourth modification, which included slow heat rise and slow cooling, produced a significantly greater failure load; Dr. E. McLaren, UCLA School of Dentistry (2008).

This preliminary testing demonstrates a potential processing modification that may minimize porcelain fractures and chipping of zirconia supported restorations. Drs. McLaren and White will be conducting additional research using various porcelains with zirconia cores.

This information has provided additional background on the unique properties of zirconia material, as well as some material handling suggestions to help increase clinicians and dental laboratories confidence in using zirconia-based restorations. 3M ESPE will continue to share more as additional research data becomes available.

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