UNRAVELLING THE ROLE OF RESIDUAL STRESS DISTRIBUTION IN THE PERFORMANCE OF BILAYERED ZIRCONIA RESTORATIONS – A NARRATIVE REVIEW

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Abstract

Bilayered zirconia restorations have gained significant popularity in modern dentistry due to their ability to combine the strength of zirconia with the natural aesthetics provided by porcelain veneers. However, the longevity and performance of these restorations can be influenced by the distribution of residual stresses within the material. This narrative review aims to explore the impact of residual stress distribution on the longevity of bilayered zirconia restorations, focusing on factors affecting stress levels, and potential failure modes and mechanisms. A Boolean search of the PubMed database was done which yielded 40 articles, of which 26 articles were included in this review. The narrative review begins with an introduction to bilayered zirconia restorations, highlighting their composition and advantages in dental applications as well as the different veneering techniques used. Subsequently, the analysis delves into stress distribution within the restoration, emphasizing its importance in determining the restoration's mechanical behaviour. Factors influencing residual stress in bilayered zirconia are explored, material properties, sintering parameters and veneering methods. Understanding these factors is crucial for optimizing stress management during restoration fabrication. In light of the influence of residual stress on restoration durability, mitigation strategies for reducing stress levels are discussed.

Keywords: Residual Stress Distribution, Veneering Techniques

Introduction

Porcelain is widely employed in dentistry to restore teeth to their functional state. Due to its desirable colour resemblance to natural teeth, porcelain has become the material of choice, surpassing the previous gold standard of metal restorations. Although porcelain fused to metal (PFM) restorations have demonstrated long-term success (1), they may fall short in terms of achieving the desired aesthetic colour compatibility due to the presence of a metal coping. This challenge has spurred the quest for all-porcelain materials capability to withstanding occlusal loading while delivering superior aesthetics. In this context, 3mol% yttrium-stabilised tetragonal zirconia polycrystal (3Y-TZP), a high-strength ceramic material, emerges as a compelling option for metal-free restorations. Its exceptional strength can be attributed to its unique phase transformation toughening (PTT) mechanism and proven to be highly biocompatible (2). However, despite its structural stability, zirconia has limitations in achieving the desired level of translucency (3). Translucency is crucial for creating restorations that closely mimic natural teeth. To address this limitation, a common practice is to apply a layer or veneer of more translucent ceramics or porcelain onto the zirconia. This veneering technique enhances the translucency of the restoration, resulting in a more natural and aesthetically pleasing appearance. A clinical investigation has demonstrated that bilayered zirconia restorations exhibit an impressive success rate of nearly 90% over a decade-long period (4). Nevertheless, a notable 8.8% of these restorations still experience premature failures (5). The porcelain laminates used in zirconia-based restorations are vulnerable to issues like chipping or delamination, which have been reported to occur as early as six months after placement (6). Intriguingly, such failures are approximately three times more frequent when compared to metal-ceramic restorations (4). Addressing these problems often necessitates not only temporary repairs but also long-term replacements of the restorations, posing challenges for clinicians and financial burdens for patients (7).

These complications have been attributed to the residual stress that can build up intrinsically when two materials are joined by heat during veneering process. High levels of residual stress have been linked to an elevated risk of porcelain delamination (8). Several factors such as the mismatch of the coefficients of thermal expansion (CTE) (9), the cooling rates of the firing process and the geometry of the assembly have been investigated. However, there is a lack of agreement of how these factors can be controlled to minimise the effects of residual stress. Hence, this study aims to offer a comprehensive narrative review of existing research focused on bilayered zirconia and its investigation into residual stress within its assembly. The objective is to enhance our comprehension of the intricate concepts of residual stress that have been developed over the last 10 years and to elucidate how adjustments in the fabrication parameters of bilayered zirconia can impact the final product.

Methodology

In this study, we conducted a comprehensive search on the PubMed database using the keywords "residual stress" and "bilayered zirconia." Boolean operators such as and, or and not were used to refine the search results. The search string used was (((bilayered zirconia) OR (veneered zirconia)) NOT (multilayered zirconia) NOT (composite resin)) AND (residual stress). Inclusion criteria included articles that have been written in English and that investigated fabrication parameters on residual stress. The research has to include a detailed description of the methodology assessing residual stress and should be published within the last 10 years. Exclusion criteria included articles that had no investigation of residual stress, and research investigation materials other than bilayered zirconia involving 3Y-TZP. Review articles were also not included in this study. After the searched articles were gathered, a spreadsheet of the titles and abstracts was made to evaluate whether the inclusion criteria had been met. After the screening of the articles, the data extraction process was done for the included articles using Microsoft Excel version 16.8 (Microsoft, One Microsoft Way Redmond, Washington, USA). Data consisting of authors' names, publication year, methodology, factors investigated, and main findings were tabled. Reasons for excluding articles were also noted.

Results

The search produced a total of 40 pertinent articles. Initial screening relied on the suitability of their abstracts for inclusion. Following this, a comprehensive review of the full texts was performed, with findings being meticulously extracted and categorized into three distinct sections. The inclusion criteria primarily targeted studies that specifically explored residual stress in bilayered zirconia, facilitating the compilation of a thorough analysis of this critical facet within the field. After this rigorous analysis, 26 out of the initial 40 articles met the inclusion criteria as shown in Table 1. The remaining 14 articles were excluded for various reasons: 11 lacked quantitative analysis on residual stress, and 3 focused on materials unrelated to 3Y-TZP.

Discussion

The Concept of Residual Stress in Bilayered Zirconia

Residual stress is a poorly understood topic in ceramics. This could be due to the complexity of the residual stress distribution three-dimensionally in the material (10). Residual stress is thought to be a hidden force within the material that influences its hardness (11). It either can be tensile or compressive. Through measurement of the hardness of samples to reference samples, stressed samples that exhibit lower hardness would be under tensile stress while materials that are harder than its reference samples would contain compressive residual stress. However, tensile and compressive stresses do not exist exclusive of each other. Materials that exhibit beneficial high compressive stress in one area may in turn exhibit deleterious tensile stress in another area within the same structure (12).

Table 1: Journal articles that were included in this narrative review.

No	Author	Year	Factor	Testing Method	Findings
1	Jikihara A. et. al. (8)	2019	CTE mismatch; Cooling rate	Finite Element Analysis (FEA)	Zero mismatch recommended. A positive CTE mismatch caused residual stresses in crown shape specimens, where the hoop stresses were compressive and the radial stresses tensile; Zirconia-compatible veneers had higher residual stress levels in both tension and compression than metal-compatible veneers.
2	Rodrigues CS. et. al. (9)	2021	Veneer - core thickness (2:1, 1:1); Cooling rate (fast vs slow)	Viscoelastic FEA (VFEM)	The 1:1 thickness ratio decreased stresses in both layers of PVZ; Slow cooling slightly decreased residual stresses in both systems. However, the cooling rate effect was more evident in transient stresses.
3	Lunt A. et. al. (11)	2019	Different testing methods	Raman spectroscopy; XRD	Tensile stresses were observed within the first 150 micron of the interface with a maximum value of ≈ 300 MPa at 50 micron from the interface; The remainder of the coping was in mild compression at ≈ − 30 MPa, with shear stresses of a similar magnitude also being induced by the YPSZ phase transformation.
4	Kim J. et. al. (13)	2018	CTE mismatch; Cooling rate	Vicker's hardness indentation test (VHIT); VFEM on crown model	Slow cooling lower residual stress; Smaller CTE mismatch reduces residual stress
5	Longhini D. et. al. (14)	2016	Cooling rate (fast vs slow); pressed and manual veneering	VHIT	Fast cooling increased compressive stress; Pressed porcelain has better flexural strength
6	Tanaka CB. et. al. (15)	2019	Cooling rate (fast vs slow)	Edge-chipping Test; FEA	Slow cooled presented with better edge chipping resistance.
7	Wendler M. et. al. (16)	2015	CTE mismatch; cooling rate (fast vs slow)	Depth-wise VHIT after sequential sectioning	Higher CTE mismatch, higher compressive stress, higher crack hindrance; Cooling rate no difference in stress and crack hindrance
8	Zhang Y. & Lawn BR. (17)	2019	CTE mismatch	VHIT; Nanoindentation	CTE mismatch smaller is best.
9	Fardin VP. et. al. (19)	2018	Bridge connector width	Nanoindentation Test	Outer third of porcelain showed the lowest hardness, indicated highest residual stress that decreased towards the interface.
10	Fukushima KA. et. al. (23)	2014	Type of material	Hole Drilling	3Y-TZP samples, surface stresses in the veneering ceramic were found to be compressive within the surface (−29 MPa). These stresses decreased with depth, becoming tensile around 1 mm from the surface (8 MPa near the framework).
11	Mainjot AK. et. al. (24)	2015	CTE mismatch	Hole drilling	CTE mismatch smaller is best; Magnitude of compressive stress inverse to CTE mismatch.
12	Sebastiani M. et. al. (25)	2015	PFM vs. porcelain fused to zirconia (PFZ)	Focused Ion Beam (FIB)	Stress near interface is compressive; Micro-defects could induce local modifications of the residual stress field, which may even locally generate a tensile stress state.

13	Wendler M. et. al. (26)	2016	Cooling rate (fast vs slow); Veneer thickness	Light birefringence; Biaxial Flexure	Cooling rate affects parallel stress more than radial. Fast cool more compressive; Veneer thickness has little influence on stress
14	Marrelli M. et. al. (27)	2015	CTE mismatch	FEA	Temperature variations 0-70 degrees can cause stress changes up to 20% of interface strength
15	Reginato VF. et. al. (28)	2018	CTE and glass transition temperature T_g	FEA	Higher T_g causes higher stress; CTE mismatch not significant to stress
16	Tanaka CB. et. al. (29)	2016	Cooling rate (slow, extremely slow), geometry (bars, semi-cylinder)	VHIT; FEA	The residual stress profiles were similar among geometries in the same cooling protocol; Extra slow cooling groups presented significantly higher tensile stresses.
17	Wang G. et. al. (30)	2014	Interface inclination angle (0 – 90°)	Modified Sandwich Test; FEA	Zirconia/veneer bilayered structure the veneer is weaker than the interface, veneer material with larger fracture toughness is needed to decrease the failure rate, coefficient of thermal expansion mismatch of the substrates can be larger to produce larger compressive stresses in the veneer.
18	Wang G. et. al. (31)	2015	Veneer - core thickness (1:2, 2:1)	FEA	Thickness ratio did not significantly affect the load-bearing capacity of bilayered beams when the thickness ratio changed from 1:2 to 2:1.
19	Freifrau Von Maltzahn N. et. al. (33)	2014	CTE mismatch	Formulae calculation based on CTE and T_g; 4-point bending	No general recommendation can be made for an optimal CTE mismatch
20	Dhital S. et. al. (34)	2020	Veneer - core thickness (2:1, 1:1, 1:2); Cooling rate, CTE mismatch	VFEM	Smaller CTE mismatch, less residual stress; Veneer thickness less, residual stress less; Slow cooling in 1:1 model show less residual stress, but more pronounced effect on transient stress
21	Al-Amleh et. al. (36)	2014	Cooling rates (fast and slow); Cusp height (1, 2, 3mm)	VHIT	Slow cooling more tensile stress, Fast cooling compressive stress; Residual stress decreases as veneering porcelain thickens; Increased stress in fast cooling, slow cooling no difference in stress
22	Benetti P. et. al. (37)	2014	Cooling rates (fast and slow); Porcelain thickness (1, 2mm)	Thermal analysis (Thermocouples); FEA	Fast cooling induces high magnitude transient stress; Metal and zirconia show similar residual stress profile. Slow cooling with thick porcelain recommended
23	Belli R. et. al. (38)	2016	Cooling rate (fast vs slow); Bonded and unbonded models (boron nitride separator)	Light birefringence; Biaxial flexure test	Fast cooling induced tensile stress towards side facing Zr core; Water diffusion into crack glass causes swelling, called water toughening effect dampening effect of residual stress.
24	Inokoshi M. et. al. (39)	2016	Sandblasting and different CTE porcelain	Field emission scanning electron microscopy (FESEM); Energy-dispersive X-ray analysis (EDX) micro-Raman spectroscopy	Sandblast damage causes phase transformation; Difference in CTE of zirconia versus that of the veneering ceramic resulted in an unfavourable residual tensile stress at the zirconia–veneering ceramic interface.

25	Jakubowicz-Kohen B. et. al. (40)	2014	Firing cycle	Profilometer to measure disc curvature	A chemically-induced volume augmentation located within the framework sub-surface near the interface could explain the sample curvature and its increase with firing time.
26	Lunt AJG. et. al. (41)	2019	Different testing methods	X-ray diffraction analysis (XRD); Focused ion beam milling (FIB)	Residual stress is tensile and is highest at the interface perpendicular to the interface; Parallel to interface tensile oscillating with compressive

Investigations on Residual Stress

Measurement of hardness

Vicker's hardness indentation testing (VHIT) is a common method for measuring material hardness illustrated in Figure 1(a). An indenter is used to create an indentation on the material, inducing crack formation along the edges of the indentations. Residual stress levels can be derived by optically measuring the crack length and comparing it to reference data (13–17). Nanoindentation testing, although less common, is also used to evaluate material hardness and residual stress distribution. A nanoindentation machine indents the sample with a pre-set load, monitoring the load magnitude and indentation depth.

Residual stress affects the force required to achieve the indentation depth, allowing for hardness calculation using established formulas (18–21). Both methods are non-destructive and provide information on material hardness. Nanoindentation offers insights into local microstructural characteristics at a smaller scale, while VHIT provides a hardness value over a larger area. Nanoindentation is less affected by defects like porosities and cracks, which can significantly impact bulk characteristics (22).

Another testing method used in hole drilling method (23, 24). In this method, the PFZ assembly is mounted in a CAD/CAM machine with a controlled drilling procedure. The sample is drilled from the surface to the interface. Strain measurements are continuously taken during the drilling process. The data obtained is calculated according to ASTM Standard Test Method E837-08 using H-Drill software (Vishay, Malvern, PA, USA). This test can provide data on residual stress in the radial dimension in a continuous path from the surface to the interface as shown in Figure 1 (b). Focused ion beam (FIB) milling and digital image correlation (DIC) have also been used in two studies to evaluate residual stress (11, 25). The basis of this technique is the elastic stiffness constant of the material. FIB milling is first used to mill a ring core pattern on the surface of the porcelain. A scanning electron microscope image is then taken. DIC is done by measuring the core size. Based on the pre-existing residual stress within the substrate, the ring core size will change, thereby, in the presence of compressive stress, the ring core will be larger.

Optical Density Measurement

Residual stress also influences the optical density of the porcelain (16, 26). By employing a polarized light beam and passing it through a thin section of the material, the wavelength of the light is modified, inducing a phase shift as shown in Figure 1 (c). Subsequently, the magnitude of residual stress can be quantified by assessing variations in the wavelengths within the polarized light beam. This approach offers a spatial representation of both compressive and tensile residual stresses distributed across the material.

Simulation methods

To validate the experimental results, finite elemental analysis models are generated to visualise and illustrate the residual stress patterns in the assembly (8, 9, 15, 27–31). This allows for 3-dimensional models to better our understanding of this matter as illustrated in Figure 1 (d). The process starts with a model creation and defining the material properties such as the elastic modulus and CTE. The models are then meshed into tiny interrelated elements, making it a finite element analysis. Mathematical equations to describe the physical characteristics of the systems are solved and with this, the residual stress is calculated. A visual representation of the stress within the bilayered zirconia is created to help understand the residual stress in the system.

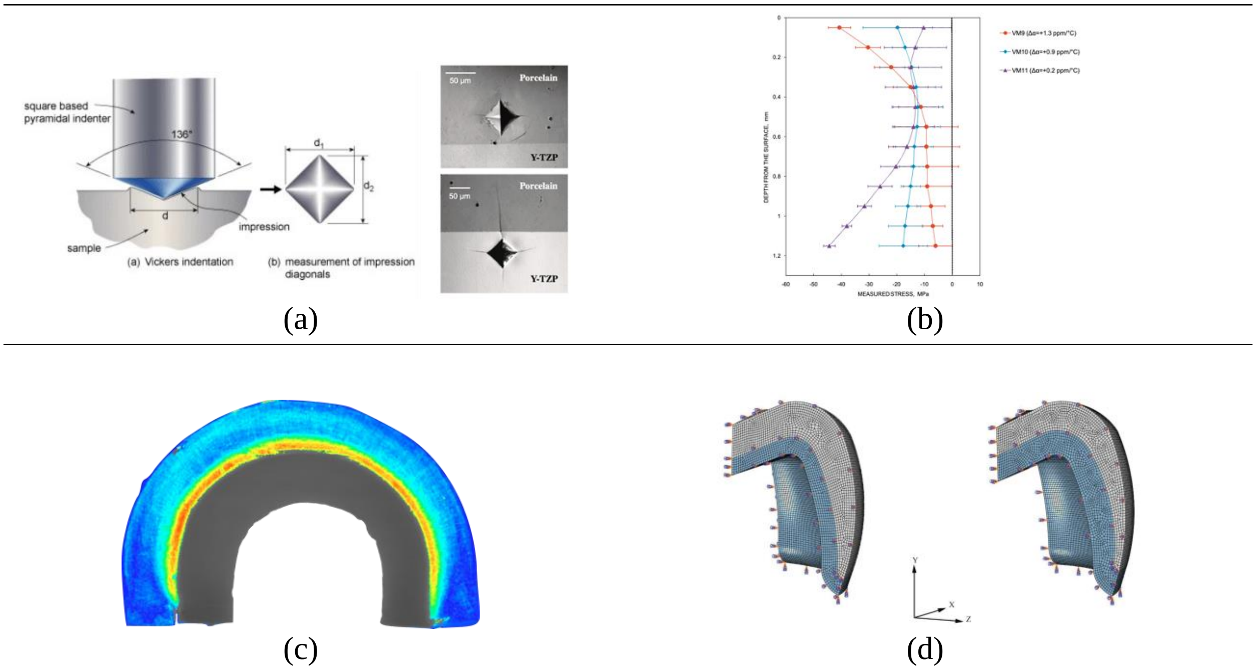

Figure 1: Testing methods used to investigate residual stress: (a) A diagram of VHIT (left) and the resultant impression for measurement adapted from (17); (b) A graph of the hole drilling stress measurement adapted from (24)(c) A diagram of the use of light birefringence for measuring optical density adapted from (26) (d) A diagram of finite element analysis used to simulate residual stress distribution adapted (9)

Fabrication Parameters Affecting Residual Stress and Their Impact on Final Products

Coefficient of thermal expansion (CTE)

The CTE refers to the rate at which materials expand and contract when it is subjected to changes in temperature during the heating and cooling process of manufacturing. When two different materials are fused, the material expands and contracts at different rates causing residual stress to be locked in residual stress within the two materials. Traditionally, with porcelain fused to metal restorations, a slight positive mismatch between the metal and veneering porcelain is taught to be beneficial to the porcelain by providing compressive residual stress which prevents cracks initiation within the porcelain. The same concept has been used in the fabrication of zirconia and its veneering porcelain counterparts with zirconia having a CTE of around $10.5\times10^{-6}/^{\circ}C$ and porcelain having a CTE of within $+1\times10^{-6}/^{\circ}C$ of the zirconia core (17, 32).

While some studies could not provide a recommendation for CTE mismatch (28, 33), most studies found that a small CTE mismatch was beneficial to the assembly compared to a larger mismatch (13, 17, 24, 34). An interesting finding in a hole drilling study found that CTE mismatch had an inverse relationship to the magnitude of compressive stress at the porcelain veneer interface which is where most delamination occurs (24). There has also been research looking into the concept of a zero mismatch between the CTE of porcelain and zirconia 12. The rationale behind it is that while compressive residual stress may be beneficial to the restoration, eliminating tensile residual stress is more essential in bilayered zirconia restorations (35). Therefore, residual stresses should be kept to a minimum. The porcelain may no longer enjoy the benefit of compressive stresses; however, harmful tensile stresses are also averted.

Cooling rates

During the firing of the veneering porcelain, the cooling rates the assembly is subjected to have been shown to influence the stress levels within the porcelain. Fast cooling refers to when the furnace is opened after the peak temperature has ended and is allowed to cool outside the furnace. Slow cooling, on the other hand, is when the furnace is kept closed after the peak firing temperature is achieved, allowing the assembly to cool slowly until the temperature is below the glass transition temperature of the porcelain before the furnace is opened. Few studies found that cooling rates affect transient stress levels more than residual stress levels (9, 16, 34, 36-37). However, there seems to be agreement that slow cooling allows for lower residual stress levels in the veneering porcelain (9, 13, 15, 34, 37). Studies found that fast cooling increased the amount of compressive residual stress that may be beneficial for the porcelain (14, 26, 36). However, studies looking at the distribution of residual stress from the porcelain surface to the interface found a pattern of stress oscillating between compressive and tensile leaving the material having lower apparent hardness at certain areas (11, 24). An increase in the compressive stress would also increase the tensile stress levels (8). In this sense, it seems better that slow cooling is employed when PFZ restorations are being fabricated.

Veneer-Core thickness ratio

Fabrication design can significantly influence the distribution of residual stress. One key aspect under scrutiny is the core thickness ratio, with investigations seeking to determine whether a thicker or thinner veneering porcelain layer results in lower residual stress. Employing FEA, this factor was thoroughly evaluated across three different ratios: 2:1, 1:1, and 1:2. Findings from two studies supported the notion that a thinner veneering porcelain layer exhibited reduced levels of residual stress (9, 34). However, one particular study did not observe a significant impact on residual stress when comparing core thickness ratios of 2:1 and 1:2 31. In light of the findings, a smaller ratio of veneer to core ratio should be recommended to reduce residual stress.

The relationship between tensile stress and hardness can be understood in the following way: as tensile stress within the porcelain layer intensifies, it tends to weaken the material, causing its resulting hardness to decrease (17). This decrease in hardness is a critical factor that renders the porcelain more vulnerable to fracturing or breaking under occlusal loads. In essence, the porcelain becomes less resistant to external forces, making it more susceptible to fractures or cracks. The factors discussed above have deepened the understanding of this correlation between residual stress distribution and changes in hardness that are crucial for designing durable and resilient porcelain structures in various applications, such as dental restorations, where material integrity is paramount to ensure long-term performance and reliability.

Conclusion

The findings of this study reveal several insights to residual stress distribution in PFZ. The concepts used for the fabrication of conventional PFM restorations cannot be applied to PFZ restorations directly as residual stress distribution is different with PFZ. Several recommendations for PFZ fabrication can be made:

i. CTE mismatch between the porcelain veneering and the zirconia core should be kept to a minimum.
ii. Slow cooling is recommended, especially when a thickness of porcelain veneering is required.
iii. A thinner porcelain veneering allows for a lower magnitude of residual stress.

While the findings of the review reveal certain advantages of controlling the fabrication parameters, these findings are derived from in vitro studies only and there lies its limitations. Clinical results validating these protocols are required in future research.

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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.

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