

Dental ceramic damage associated with incorrect laboratory procedures

Magdalena Szawiola-Kirejczyk^{1,A–F}, Karolina Chmura^{2,A–F}, Wojciech Ryniewicz^{2,A,C–F}

¹ Department of Prosthodontics, University Dental Clinic, Cracow, Poland

² Department of Prosthodontics and Orthodontics, Dental Institute, Jagiellonian University Medical College, Cracow, Poland

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Address for correspondence

Karolina Chmura

E-mail: k.chmura@uj.edu.pl

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Abstract

Ceramic is a commonly used material in dentistry for reconstructing missing teeth or their tissues due to its biocompatibility, durability and excellent esthetic properties. Despite these advantages, the ceramic restoration damage remains a significant clinical problem. Its causes can be divided into clinical and laboratory factors. The most known include uneven occlusion, improper preparation, trauma, or parafunctions. This study focuses on characterizing less known laboratory causes of ceramic restoration damage. We reviewed the current literature available in the PubMed and Scopus databases. On the basis of 63 selected studies, 3 basic causes of damage were identified: excessive stresses between the framework and ceramic veneering, poor quality of the connection between the facing layer and the substructure, and defects resulting from the nature of the ceramic material such as defects in the ceramic layer, brittleness and lack of flexibility. The stages of the manufacturing process of various permanent ceramic restorations were presented. By controlling these procedures, we can eliminate the errors, resulting in long-term effective functioning of the ceramic restorations.

Key words: ceramics, crowns, zirconium oxide, dental restoration failure, metal–ceramic alloys

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Introduction

Ceramic materials are commonly used in dentistry. Metal–ceramic restorations have been considered the “gold standard” in prosthetic rehabilitation of damaged tooth structures since the late 1950s. They integrate the high strength of metal substructure with the ceramic veneering esthetics.¹ Over the past 30 years, the growing demand for highly esthetic and natural-looking prosthetic restorations has led to the development of new ceramic materials with excellent mechanical strength and a high degree of biocompatibility, which enabled metal base elimination.² However, despite continuous material and technological progress, the survival rates of ceramic restorations invariably depend on the correctness of clinical and laboratory procedures.

Ceramic restorations are an effective and long-term prosthetic reconstruction. A systematic review assessing the durability of prosthetic crowns over a 5-year period has shown that conventional metal–ceramic restorations show a similar success rate (95.7%) to lithium disilicate all-ceramic restorations, leucite-reinforced glass ceramics (96.6%), glass-infiltrated alumina (94.6%), and zirconium oxide (93.8%). However, the survival rate of feldspathic crowns was lower (90.7%), particularly in the posterior region (87.8%).³

In addition, a systematic review demonstrated a 94.4% survival rate for metal–ceramic bridges over the 5-year observation period. It was higher than that of all-ceramic bridges made of reinforced glass ceramics (85.9%), glass-infiltrated aluminum oxide (86.2%) or zirconium oxide (90.1%).⁴

Despite many unquestionable advantages, ceramic restorations may deteriorate over time. The main cause of distant complications is ceramic veneering damage, so-called chipping. The authors noted that zirconium oxide (3.1%) and metal–ceramic (2.6%) crowns showed a higher incidence of ceramic chipping, while crowns made of leucite ceramics and lithium disilicate showed a higher frequency of framework fracture (2.3%) over the 5-year period.² On the other hand, in the case of bridges after the same period, the frequency of ceramic chipping was the highest for ceramic restorations on glass-infiltrated alumina (31.4%) and densely sintered zirconium oxide (20.4%). All-ceramic restorations made of reinforced ceramics glass (10.1%) and alumina infiltrated with glass (12.9%) also showed the highest fracture frequency. It is important to note that these are objective findings and not subjective evaluations.⁴

There are many classifications of ceramic damage available in the literature.^{1,5,6} One of them is the classification of Michalakakis and Agustín, which divides them into 3 damage types: cohesive, adhesive and adhesive-cohesive. Cohesive damage is characterized by chipping within the veneering ceramic layer, adhesive damage is characterized by chipping with the prosthetic restoration base exposed, while adhesive-cohesive damage is a combination of 2 types of ceramic damage.^{1,5}

Heintze and Rousson classified the damage according to its size and reparability. Grade 1 refers to superficial damage. It is a small chip, which can be fixed just by polishing the ceramic restoration surface. Grade 2 is a moderate chipping of the veneering ceramic. It requires intraoral repair with a composite resin. Grade 3 is an extensive damage of veneering ceramic, which requires the replacement of the damaged fixed prosthesis for both functional and esthetic reasons.⁶

In addition, we can also include cracking of the substructure and span of the bridge as a type of damages. A study by Saito et al. showed that zirconia-based ceramic restorations failures are most often cohesive (88.8%).⁷ Also, Agustín et al. observed that the most common type of failure for zirconia-core ceramic restorations was cohesion (71.66%), compared to metal–ceramic restorations, all of which showed adhesive failure.¹

On the other hand, literature reviews conducted by Heintze and Rousson, Raigrodski et al. and Anusavice show that the most common types of permanent dentures chipping are grades 1 and 2, which are esthetic defects often unnoticed by the patient and not associated with the failure of prosthetic reconstruction.^{6,8,9}

Unlike clinical issues, which are directly controlled by the dentist, problems related to the laboratory process are not part of everyday practice. The purpose of this work is to identify errors that may occur during the laboratory stage of execution, which can result in premature loss or damage of permanent restorations such as crowns and bridges.

Materials and methods

This review is based on a literature search conducted in the PubMed, Embase and Scopus databases. Article published between 2002 and 2021 were included. We performed a combined free text term and medical-subject heading (MeSH) search. Our inclusion criteria were based on a PICO (Patient, Intervention, Comparison, Outcome) strategy. The search strategy was developed in stages, incorporating the type of patients who use fixed partial



Fig. 1. Search strategy

dentures (crowns and bridges), the type of materials used (all-ceramic, metal–ceramic, zirconia, and glass–ceramic), and the presence of complications or restoration failure. The full strategy is presented in Fig. 1.

The combination in the builder was set as “P & I AND C AND O”. Exclusion criteria were defined as follows:

hybrid material restorations, case studies and languages other than English.

Two independent researchers performed the selection of the studies. In the 1st step, titles and abstracts were screened for relevant articles. In the 2nd step, full texts were assessed. The results are summarized in Fig. 2.

Results

The evaluation included 63 articles after final eligibility assessment, selected from 2,679 papers that met the key-word criteria during the literature review.

Residual stress occurring during laboratory procedures is a crucial factor in the damage of ceramic restorations. The factors affecting the residual stresses of veneers include the functional stresses, thermal expansion coefficients of the framework and ceramic veneering, firing temperature and cooling time, geometry of the ceramic restoration, processing technique of the zirconia framework, and choice of veneering method and framework material for the fixed denture. It is important to consider all of these factors when designing and fabricating dental restorations. The bonding quality of veneering ceramic to the framework and the poor properties of the veneering ceramic are important factors that influence the survival rates of restorations.^{10–13}

Based on the literature review, the following laboratory factors leading to ceramic damage were distinguished and presented in Fig. 3.

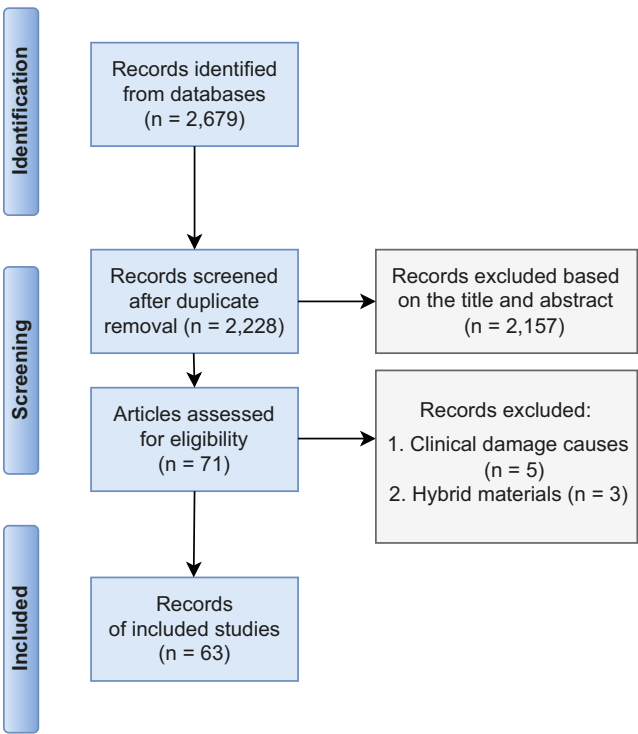


Fig. 2. Article selection process

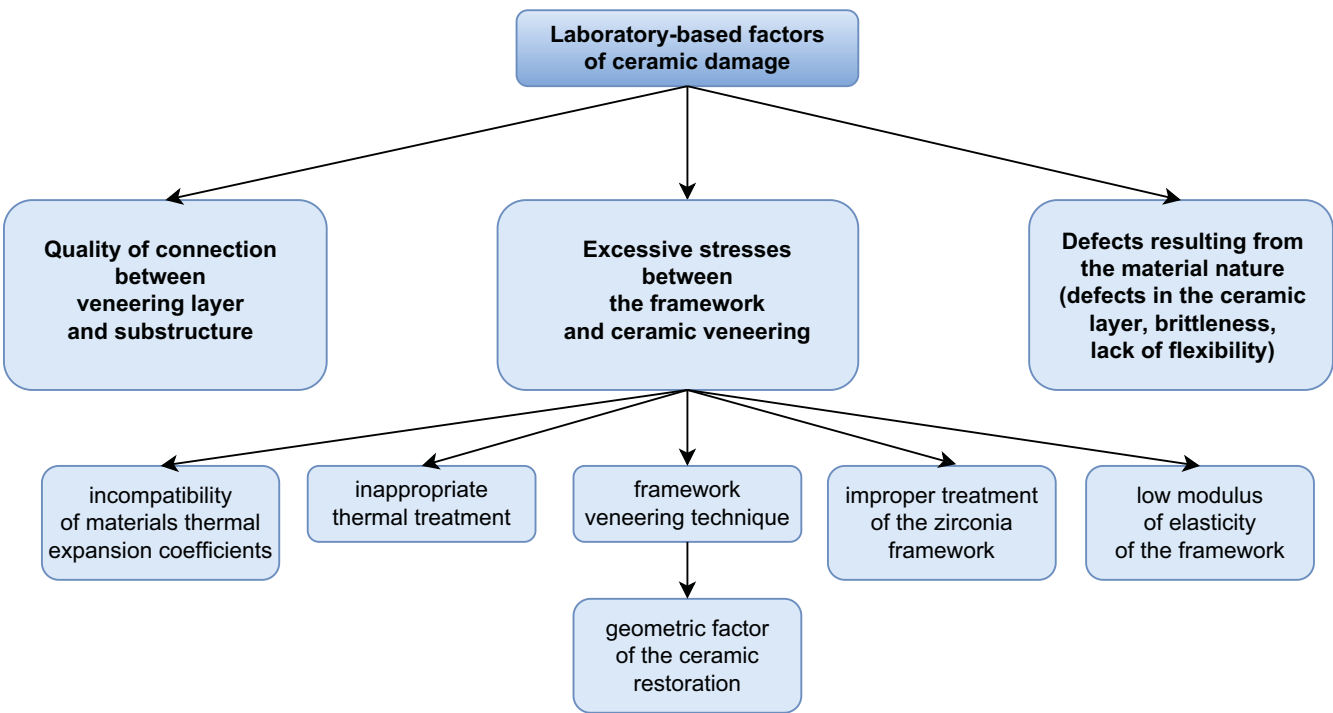


Fig. 3. Laboratory causes of ceramic damage

Excessive stresses between the framework and ceramic veneering

Incompatibility of thermal expansion coefficients of materials

Studies have found that compatibility of thermal expansion coefficients (coefficient of thermal expansion (CTE)) between veneering porcelain and the metal or ceramic substructure is critical to avoid formation of cracks after the firing process.¹⁴ Ceramic coefficient of thermal expansion should be slightly lower than the CTE of the core material. As the weaker veneering ceramic cools, a small compressive stress, known as residual compression, is generated. This compensates for the tensile stresses that arise from the mechanical load of the prosthetic restoration.^{14,15}

A study by Juntavee and Dangsuan evaluating the effect of a veneering ceramic type with different CTE on a zirconia framework showed that a veneering ceramic CTE $0.77\text{--}0.87 \times 10^{-6}/^{\circ}\text{C}$ lower than the CTE of zirconia resulted in the desired residual compressive stress. It provided favorable bonding strength between the fired ceramic and the zirconia.¹⁶ In the case of metal–ceramic restorations, the CTE of the metal alloy lower by $0.5 \times 10^{-6}/^{\circ}\text{C}$ than the thermal expansion coefficient of the fired ceramic was found to be the most favorable.^{17,18} Much higher substructure CTE than CTE of the ceramic veneering layer can result in a compressive stress during cooling process. These stresses run parallel to the framework and may lead to delamination of the veneering ceramic from the framework. However, when the CTE of the framework is definitely lower than that of the veneer, the tensile stresses increase, which initiates the formation of cracks running on the surface of the veneering ceramics.¹⁴

A mismatch of the CTEs of the veneering ceramic and the zirconia framework above 10% has been proven to cause porcelain fracture.¹⁴ The coefficients of thermal expansion discrepancies may be more critical for all-ceramic restorations compared to metal–ceramic restorations. The former, due to the higher stiffness and brittleness of the ceramic substructure, do not tolerate tensile stresses.¹⁹ Additionally, the study by Swain showed that the higher rates of veneer ceramic chipping in zirconia ceramic restorations may be due to residual stresses resulting from a greater thermal mismatch between the zirconia core and the veneer ceramic. This phenomenon may be caused by the poor thermal conductivity of zirconium compared to the metal alloy.¹⁴

Inappropriate thermal treatment

In order to obtain the correct anatomy and esthetics of ceramic restorations, the manufacturing process consists of several stages, during which successive layers of ceramics are applied. Each layer undergoes sintering

cycles at a temperature well above the glass transition temperature of the veneering ceramic.¹⁹ In order to obtain satisfactory results, it is extremely important to follow the manufacturer's guidelines regarding time, temperature, number of firings, and the recommended porcelain cooling protocol.

Saini et al. demonstrated on the basis of experimental studies that the firing temperature of dental ceramics lower than recommended by the manufacturers causes superficial and deep porosity. The ceramic inhomogeneity reduces the strength of the material.²⁰

It is equally important to follow the correct cooling protocol. According to Swain, the rate of cooling after each firing cycle affects the amount of residual stresses developing in the ceramic restoration.¹⁴ Restorations that are cooled by immediately opening the furnace after firing are exposed to thermal shock. The outer surface of the porcelain solidifies and shrinks earlier, while the inner part is still at a higher temperature. After cooling, the internal temperature drops, and the solid outer surface of the porcelain prevent the shrinkage of the inner layers. It results in residual tensile stresses locked into the material layers.²¹ Also, an excessively prolonged cooling protocol from sintering temperature to room temperature may weaken the bond strength between the veneer and the framework. It generates residual tensile stresses resulting from the elastic relaxation of the glass phase contained in the veneering ceramic.²²

Slow cooling protocol after the last firing program is particularly important in the fabrication of zirconia-based ceramic restorations because unlike metal alloys (40–200 W/mK) and aluminum oxide (30 W/mK), glass ceramics (3–4 W/mK) and zirconia (1–4 W/mK) have a low thermal conductivity.¹⁹ The ceramic framework retains heat for a longer period instead of transferring it to the veneering ceramic. During the firing and cooling process, unfavorable temperature distribution occurs. Internal stresses arise in the facing material, which initiate the formation of cracks with extensive propagation. In the case of a thick zirconia framework, test results suggest a slow cooling protocol below the glass transition temperature of the fused ceramic to compensate for the slow temperature transition through the zirconia. This procedure prevents the formation of large temperature gradients that generate residual stresses in the porcelain layer.^{14,23,24} Tang et al. based on statistical analysis showed that slow cooling does not increase the average failure load in the case of porcelain crowns on a thin zirconia framework.²⁵

Framework veneering technique

In the case of ceramic crowns, various methods of veneer production can be used – the conventional technique of layering, pressing, as well as the latest technique of making a ceramic veneer in CAD/CAM technology.^{12,26}

Och et al. suggest that the method of veneering has a more significant impact on fracture toughness than the thickness of the framework or the material used in its execution. They investigated the effect of the metal and zirconia core veneering technique on ceramic fracture. The hot pressing technique (55.27 MPa) showed a higher fracture toughness than the conventional layer method (41.52 MPa).¹² Pressed ceramics have a more homogeneous structure, with fewer defects (pores, micro-cracks, scratches) due to the more controlled method of production from ready-to-use blocks. Traditional layer firing is a more sensitive technique where unintended errors may occur. Incorrect powder/liquid ratio, introduction of air bubbles during mixing the suspension, overdrying or firing of over-soaked ceramics, as well as time and temperature fluctuations during successive firings layers can be such errors. They can result in formation of porosity and microcracks in sintered ceramics, which lead to material damage.^{12,27}

Consistent with a previous study, Christensen reported that hot-pressed fixed prostheses had a lower fracture rate over a 2-year observation period for both zirconia and metal–ceramic restorations compared to the traditional method.²⁸ In vitro studies by Beuer et al. showed better mechanical properties of restorations based on zirconium oxide with lithium disilicate ceramic veneers made in the CAD/CAM technology compared to conventionally veneered crowns and pressing technology.²⁶

Improper treatment of the zirconia framework

Due to its high flexural and fracture strength, zirconia ceramics are one of the most popular materials used for substructures in all-ceramic restorations.²⁹ Zirconium oxide used in prosthetics is in form of sintered or pre-baked blocks/discs that are milled in the CAD/CAM system. Zirconia is a polymorphic material. It occurs in 3 allotropic forms: monoclinic (below 1,170°C), which changes with the temperature increase into the tetragonal form (1,170°C – 2,370°C) and to regular (cubic) at 2,680°C, corresponding to the melting point of zirconium oxide. The tetragonal form is the most advantageous in terms of biomechanics. To stabilize it during cooling to room temperature, 3 mol% yttrium oxide (Y_2O_3) is usually added.³⁰

The mechanical properties of yttria-stabilized zirconia (3Y-TZP) depend on the grain size (0.2–1 μ m) and their size depends on the sintering temperature. Compared to other ceramic materials, zirconia ceramics exhibit excellent mechanical properties due to the strengthening transformation mechanism. This phenomenon occurs through the local transformation of the tetragonal phase into the monoclinic form under the influence of the spreading microcrack. During phase transformation, grain volume increases (4.5%). Compressive stresses arise around the transformed particles, which effectively prevent further propagation of the microcrack, increasing the fracture toughness of the material by closing the cracks.³¹

Despite good mechanical properties and biocompatibility, the unfavorable feature of zirconia is its susceptibility to the so-called “aging”, also referred to as “low temperature degradation” (LTD). The essence of this phenomenon lies in the spontaneous transformation of the tetragonal form into the monoclinic, stable at low temperatures. The cause of premature “aging” and the loss of the ability of the material to prevent the spread of cracks is the oral cavity pH environment, moist and variable temperature connected with external stresses.³²

Such stresses can be a result of abrasive blasting with aluminum oxide (used to improve the bond strength between veneer and the framework), or of the final framework correction with thick diamond coating grinding and polishing tools with an inadequate water cooling. Improper treatment of the core triggers stresses that lead to a spontaneous phase change from tetragonal to monoclinic at the point of overheating. Phase transformation is accompanied by an increase in grain volume (4%), which leads to loosening of the microstructure and degradation of the material surface to a depth of 80–110 nm. In addition, there is a change in the coefficient of thermal expansion (the tetragonal phase has a CTE of $10.8 \times 10^{-6}/^{\circ}C$, the monoclinic phase – of $7.5 \times 10^{-6}/^{\circ}C$) in the vicinity of overheating. Tensile stresses arise which weaken the bond between the veneering ceramic and the zirconia core. The described mechanism can lead to veneer chipping but also cracking of the zirconia framework.^{11,30,32} Some studies show that zirconia framework sandblasting does not improve the bonding strength between veneer and the base^{33,34} and may reduce its strength by up to 30%.³⁵

Low modulus of elasticity of the framework

The parameter that influences the long-term clinical success of porcelain restorations is the Young's modulus (E) of the substrate supporting the ceramic. Materials have their constant, strictly defined coefficient of elasticity, which is a measure of resistance to elastic deformation. In other words, the higher the modulus of elasticity of the porcelain support structure, the stiffer the support for brittle ceramics and the greater the resistance to deformation under load. For compound crowns, a low-modulus glass–ceramic veneering porcelain (E ~70 GPa) is supported by a stiffer metal substructure or a ceramic core (E 200–300 GPa) that can withstand high occlusal loads.^{36,37} The use of an alloy substructure with a low modulus E will cause deflexion even under a small load due to the easy elastic deformation of the metal. Tensile stresses develop in the veneer layer, resulting in a greater tendency for the ceramic veneer to crack and chip.^{38,39}

Single-layer (monolithic) ceramic restorations are adhesively bonded to a less rigid material such as dentine (E 18 GPa) or dentin replacement composite (E 15–20 GPa), which flexes under load, providing poor ceramic support. It is generally believed that low-strength glass–ceramics

require considerable thickness (typically 1.5–2 mm) to withstand the tensile stresses on the inner surface of the cementation caused by crowns bending under occlusal loading. In general, ceramic fracture may start at the upper occlusal surface, the concave cementation surface or at the margins of the ceramic restoration. It has been noted that in the case of monolithic ceramic restorations, the type of ceramic fracture is determined by the ceramic layer thickness. In the thin ceramic layers (below 1 mm), the stiffness of the substrate plays a significant role and radial cracks predominate under destructive loads. This damage type starts on the inner surface of the ceramic (cementation surface), where the tensile strength is greatest, and then spreads through the material to the outer surface, eventually leading to a critical fracture of the restoration. With the increase of the ceramic thickness above 2 mm, the dominance of the radial crack begins to disappear. Cracks that appear on the occlusal surface are responsible for ceramic chipping. Unlike radial fracture, contact stress damage on the occlusal surface is not dependent on the modulus of elasticity of the substrate supporting the ceramic.^{36,40}

Geometric factor of the ceramic restoration

Crowns

The spatial structure of the crown affects the distribution of stresses that occur during chewing and thus plays a significant role in the ceramic resistance. It is a well-known fact that the occlusal forces acting along the long axis of the teeth are most favorable. Therefore, prosthetic restorations should be designed to minimize the lateral forces. Horizontal forces can be eliminated by locating the cusp tips on the occlusal surface in the central sulcus and not on the marginal ridges.⁴¹ It is recommended to avoid sharp cusps near the edges of the crowns to prevent their damage.⁴² They create stronger contact in axial loading and distribute forces over a smaller area. Increased local stresses predispose to the initiation of cracks and subsequent chipping of the ceramic.⁴³ However, the geometric factors above the crown are limited by the spatial constraints imposed by opposing and adjacent teeth.

Bridges

Geometric features of the prosthetic bridge, such as connector size, shape, pontic spread, and the curvature radius at their intersection, have a significant impact on the stresses concentration arising from the occlusal load. Occlusal loading creates a bending moment along the entire length of the bridge.⁴⁴ The connector between the crown placed on the abutment tooth and the pontic is most exposed to damage.^{44–50} This is due to the relatively small thickness of the connector compared

to other elements of the bridge.⁴⁷ Therefore, tensile stress concentration occurs in the gingival region of the connector, which leads to chipping of the brittle veneering ceramics and fracture of the prosthetic structure in this place.⁵⁰ This fact is confirmed by the results of experimental *in vitro* tests and factual analysis of damaged prosthetic bridges.^{45,49,51} Therefore, it is advisable to keep the minimum diameter of the connector, which, according to the literature, may reduce the probability of damage to less than 5% over 20 years of its operation.⁴⁴ Furthermore, with increase in bridge length, the greater the size of the connecting surface should be introduced. In the case of bridges on a metal foundation, the minimum diameter of the connector is 6.25 mm².⁴⁸ On the other hand, for the majority of all-ceramic systems, connector areas of 9 mm² and 16 mm² have been proposed.^{47,49,50,52}

However, the height of the connector (in the occlusal–gingival dimension) should be as large as possible, taking into account anatomical limitations (interstitial space, height of clinical crowns) and esthetic considerations.⁴⁹ In addition, it has been found that the fracture load values of permanent partial dentures increase with the size and with the radius of connectors curvature.^{49,51} Oh and Anusavice confirmed this in their study, where smaller connector radii increased stress concentration. They showed that with the increase of connector curvature radius in the gingival fissure from 0.25 mm to 0.90 mm, the average breaking load of the prosthetic restoration increased by 140%. Thus, the likelihood of breakage can be reduced by using a connector with a radius of curvature of about 0.9 mm.⁵¹

Furthermore, the shape of the connector affects the number of stresses generated during the occlusal load. It has been found that a circular or oval cross-section of the connector shows less stress and better reinforcement than a square one.⁴⁶ From the biomechanical point of view, short bridge pontics are advantageous. Under occlusal loads, pontics bend minimally. Deflection increases with length and may lead to ceramic chipping or connector breakage. Large-span bridges, especially in the posterior region, are more prone to clinical failure.^{53,54}

Thickness of the veneering ceramic

The thickness of the veneer affects the occurrence of stress between the framework and the ceramic veneer.¹⁴ From the clinical point of view, a ceramic veneer thickness from 0.8 mm to 1.2 mm is considered optimal. Its variation depends on the opposing tooth, the occlusal space, preparation, and the complex anatomy of the ceramic crown, which has areas such as cusp and axial walls of varying thicknesses of porcelain.^{55,56} Ceramics with inhomogeneous thickness over the entire veneered surface, exceeding 2 mm, have been associated with reduced strength of the prosthetic restoration due to the susceptibility of the ceramic to subsurface residual

stresses.^{14,57} This was confirmed by Figueiredo et al., who studied the flexural strength and crack propagation in zirconia samples veneered with fluorapatite leucite glass ceramic of different thicknesses (1, 2 and 3 mm). The samples with the thinnest veneer (1 mm) presented the highest bending strength. As the thickness increased from 1 mm to 3 mm, the gradients of thermal stresses between the zirconia and the veneer increased significantly. In the samples with 2-mm veneering porcelain, chipping was observed within the veneering ceramic layer. The most serious damage and chipping of the veneering ceramic with exposure of the zirconia core was observed in the 3-mm veneering samples.¹⁰ This finding is in line with the Swain's study that thick layers of low diffusion veneering ceramics, such as Y-TZP, cause high tensile stresses generated during firing and cooling of the porcelain.¹⁴ In contrast, Badran et al. showed that the fracture toughness of 1.5-mm incisal veneer crowns was significantly higher than 3-mm incisal veneer crowns for both zirconia and metal alloys.² Cohesive spalling in the veneering ceramic layer is the dominant type of damage when using an uneven, thick layer of porcelain for veneering prosthetic restorations, both on zirconia and metal substructures.^{2,58}

Ceramic restoration framework design

One of the causes of ceramic fractures is an improper framework design. It is important to prepare the framework so that it is in oval in shape, without undercuts and sharp edges that create stress points during chewing and subsequent fracture of the ceramic.³⁶

Another factor affecting the success of a ceramic restoration is the thickness of the framework. According to the recommendations, thickness of the metal framework cannot be less than 0.3 mm, and the thickness of the Y-TZP ceramic should not be less than 0.5 mm.⁵⁹ As shown by the research results of Oh et al., the base material, but also its thickness, affect the flexural strength of the ceramic restoration. The tested samples with a metal core of 1-mm thickness showed a higher fracture toughness of the veneering ceramics (61.87 MPa) than the samples with a metal core of 0.5-mm (47.11 MPa) and 1-mm zirconia (49.97 MPa). It was noted that in the case of zirconia core samples, increasing the minimum recommended thickness of 0.5 mm (46.82 MPa) to 1.0 mm (49.97 MPa) did not significantly change the fracture toughness. In contrast to the metal-core samples, it was found that an increase in the thickness of the metal substructure increases its stiffness, reducing the bending and tensile stresses of the porcelain veneer under occlusal loads.¹²

The geometry of the framework is another factor that affects the strength of ceramic restorations. The substructure, both metal and ceramic, should take into account the anatomical structure of the future tooth crown. Ceramic layer applied both in the area of cusp and fissures

should have a comparable thickness. A substructure with a non-anatomical shape and uniform thickness will lead to uneven support of the cusps or the incisal edge, which transfers the masticatory loads to the veneering ceramic instead of the substructure.^{60,61}

Research indicates that masticatory stresses may be greater at the gingival margin than at the occlusal surface.⁶² Therefore, an anatomic framework without anatomical support may not be a sufficient support for the veneering porcelain in the case of zirconia-based ceramic restorations. It was suggested that the anatomical framework should be modified by adding buccal and/or lingual support structures and increasing the thickness in the proximal area to reduce the amount of porcelain veneering in the non-visible area.^{58,63} In contrast, other studies have shown that the modified framework design did not improve the fracture toughness of the restorations.^{64,65}

Metal–ceramic restorations traditionally have a narrow metal margin. The construction of the restoration margin creates a grayish shadow in the gingival area, known as the “umbrella effect”. In order to improve the esthetics, restorations with a ceramic margin were introduced. When designing a crown with a ceramic gingival margin, it should be remembered that the substructure should rest on the shoulder of the tooth and not on its veneer. The crown substructure should be designed to reach the inner edge of the shoulder. In this way, functional support of the substructure on the abutment can be achieved. An unsupported ceramic step may not be able to withstand the stresses that occur during cementation and mastication.⁶⁶ Yoon et al. found that the increase in unsupported porcelain caused by the reduction of the metal margin reduces the restoration breaking strength. The fracture toughness of metal–ceramic restorations with a ceramic shoulder and reduced substructure structure are influenced by the number of ceramic firings increasing with the weight of the edge porcelain (possibly increasing the thickness of the metal oxide layer), microcracks or porosity of the porcelain edge, marginal leakage, and loss of ceramic support through the framework.⁶⁶

Quality of connection between veneering layer and substructure

The durability of ceramic restorations depends on the quality of the bond between the substructure and the ceramic. The bonding mechanism between veneering ceramics to the ceramic substructure is not fully understood, as is the bonding mechanism between ceramics and the metal alloy.⁶⁷ The bond strength between zirconia and porcelain is weaker than that between metal and porcelain.³³ This is confirmed by Fischer et al. who showed that mechanical surface treatment by sandblasting does not improve the adhesion between veneering ceramics and zirconia frameworks.³⁴ At the same time, the viscoelastic

properties of the veneering ceramics during sintering and the appropriately selected coefficients of thermal expansion can affect the adhesion between the ceramic and the zirconia core.⁶⁸

When metal alloys are veneered with ceramics, the following factors are responsible for the bond between these materials: compressive stress resulting from the difference in material shrinkage, mechanical bond (microretention) and chemical bond (oxide layer formed on the metal surface).⁶⁹ According to ISO 9693 standards, the durability of a metal–ceramic restoration is sufficient when the metal–ceramic shear stress is greater than 25 MPa. To achieve a good mechanical bond, the metal substructure is initially prepared with carbide cutters and then sandblasted with aluminum oxide according to the manufacturer's recommendations. The purpose of the above treatment, apart from developing microretention and increasing the wettability of the metal with porcelain, is to clean it. Therefore, improperly performed multidirectional grinding instead of the recommended unidirectional grinding, as well as improper abrasive blasting, will result in the retention of impurities and air on the substructure surface. The impurities remaining in the metal layer are decomposed during firing, creating gas bubbles at the metal–ceramic interface, which reduces the strength of the porcelain.⁷⁰ In addition, before applying the first layer of porcelain, it is recommended to clean the metal surface with a steam jet. As indicated by Lahori et al., regular inspection of the steam generator is important, as impurities in the steam can cause a reduction in the bond strength between metal and ceramics.⁶⁷

The most important mechanism affecting the ceramic–metal bond is the chemical bond between the ceramic and the oxide layer on the surface of the metal substructure.⁷⁰ An oxide layer is formed on the metal surface by heat treatment before firing the first ceramic layer (opaquer). The oxidation process initiates the formation of oxides, but also removes impurities from the metal framework. The thickness of the metal oxide layer is extremely important for the quality of the metal–ceramic bond. Their lack or too thin layer due to improperly conducted oxidation process for a given alloy, as well as too thick layer of oxides resulting from the application of too thick first layer and improper technique of opaquer firing cause adhesive type chips with exposure of the metal surface.⁷¹ Sandblasting of a substructure need to match type of alloy used to its creation. Research has shown that nickel- and cobalt-based alloys tend to form a thick layer of oxides. Before applying porcelain, the metal framework should be sandblasted to remove excess oxides. Failure to do this may result in separation of the ceramic from the metal. In contrast, alloys based on a noble metals, such as gold alloys or palladium, form thinner oxide layers. Therefore, it is a mistake to sandblast them after the oxidation process.^{67,70,71}

Defects resulting from the material properties

One of the main factors contributing to the clinical problem of veneer chips is the low strength of the veneer ceramics. Extremely important parameters describing the mechanical properties of ceramics are the modulus of elasticity, fracture toughness and bending strength. Fracture toughness, expressed by the critical stress intensity factor (K_{IC}) at which the current defect begins to increase, indicates the intrinsic ability of the material to resist rapid crack propagation and consequent critical failure. The values (K_{IC}) are variable and depend on the size, number and location of material defects, and environmental factors, such as humidity and temperature.⁷²

A study by Borba et al. has shown that the microstructure of a ceramic significantly influences its mechanical properties. The glassy phase of the ceramic has the typical properties of glass. It makes the ceramic translucent, but it is also the cause of its brittleness and non-directional cracks pattern. In contrast, the crystalline phase, depending on the size, number and geometry of the crystals, provides the ceramic material with strength, stability during firing and resistance to stress. Thus, it should be emphasized that the higher the percentage of crystals in the ceramic structure, the greater the difficulty of defect propagation (slow crack growth) and its flexural strength. It is well known that ceramic and metal alloy substructures for crowns or bridges require the use of veneering ceramics to achieve excellent esthetics.

Borba et al. found that feldspar-based and leucite-reinforced veneering ceramics exhibited low fracture toughness (0.7 MPa m^{1/2}) and flexural strength (154 MPa and 160 MPa, respectively) compared to polycrystalline ceramics of yttrium oxide stabilized zirconia (Y-TZP) (6.5 MPa m^{1/2}, 700–1,200 MPa), glass infiltrated zirconia-based alumina ceramic (IZ) (3.6 MPa m^{1/2}, 440–620 MPa) and polycrystalline alumina (AL) (3.6 MPa m^{1/2}, 500 MPa). The susceptibility of veneering ceramics to damage occurring at low loads can be attributed to their microstructure, as they consist mainly of a glass phase (55–65% in feldspar ceramics) which is susceptible to crack propagation. The low porosity of polycrystalline ceramics of 0.1–0.2% compared to glass ceramics of 2.6–2.7% has an impact on good mechanical strength. The homogeneity and lower porosity of alumina and zirconium dioxide ceramics can be related to the high content of crystals in the structure. Their production from ready to use blocks in the CAD-CAM technology, in which there are no errors appearing in the ceramic sintering technology, also decreases their damage rates.^{13,73}

Conclusions

Despite the favorable clinical prognosis, damage to ceramic restorations is a major problem in everyday clinical practice. Ceramic chipping in the anterior part of the dental


arch is a serious esthetic problem, while in the lateral a functional one. Management of damaged restorations requires knowledge of the etiology of this phenomenon. Based on the analyzed literature, ceramic damage is associated with errors that may occur at any stage of the laboratory process. In order to avoid them, it is recommended to select the right materials and, above all, to control the precision and quality of the technological process.

New technologies and ceramic materials are being developed to increase the strength of ceramic restorations and reduce complications. The latest achievement in the fabrication of ceramic restorations is the use of highly translucent zirconium dioxide (HT), as it allows the fabrication of esthetic, monolithic restorations without the need for veneering. Monolithic zirconia restorations are easier to fabricate than traditional ones. The limited number of steps reduces the possibility of laboratory errors. A single-material structure eliminates many of the problems mentioned in this article, such as the quality of the bond between the veneering layer and the substructure or excessive stress between different materials. At this point, according to the literature, we can distinguish problems related mostly to excessive reduction of the thickness of the restoration and to insufficient esthetic properties.

There are limited data describing long-term survival rate and complication types of monolithic zirconia restorations. Due to their relative novelty and the different types of materials, further long-term in vitro observations are needed before general conclusions can be drawn.^{74–76} Another material worth mentioning is hybrid ceramics, which combines the advantages of glass ceramics and composites, and whose undeniable advantage is the possibility of repairing the prosthetic restoration directly in the patient's mouth.^{77,78} Technological and material advances make it possible to reduce the number of errors made during laboratory procedures. However, it does not exempt the dentist from knowledge of basic laboratory procedures and the associated damage to ceramics. Knowledge of these processes may allow the clinician to control and eliminate them more precisely, resulting in a better long-term prognosis of the fabricated restorations.

ORCID iDs

Karolina Chmura  <https://orcid.org/0000-0002-6174-3938>

Wojciech Ryniewicz  <https://orcid.org/0000-0002-2309-4455>

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