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Effect of Aging on Morphological and Optical Properties of Directly Printed Orthodontic Aligners: A Narrative Review

Ibrahim Yawoz Abdulkarim (1) *
Sara M. Al-Mashhadany (2)

(1,2) Department of Orthodontics, College of Dentistry, University of Baghdad, Baghdad, Iraq.

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***Corresponding Author:**
Email:
ibrahim.abd2303m@codental.uobaghdad.edu.iq
M.Sc. student, Department of Orthodontics, College of Dentistry, University of Baghdad, Baghdad, Iraq.

Abstract

Clear aligners are a popular aesthetic orthodontic treatment, but they are costly and complicated due to the manufacturers' involvement. To address this issue, dental practitioners have adopted in-house 3D printing technology as a cost-effective solution. To solve the limits of conventional manufacturing techniques, recent efforts have been undertaken to directly 3D print clear aligners utilizing a biocompatible material. The workflow for designing and printing aligners involves error-prone steps that require meticulous analysis and examination through scientific study. Testing is necessary before replacing of traditional thermoformed aligners with 3D-printed alternatives. It is possible to tailor aligners to meet individual clinical requirements owing to the adaptable design features of printed aligners. This review outlines the effect of aging on the morphological and optical properties of directly printed orthodontic aligners. Publish articles about the topic from 2010 to 2025 were around 27 articles. The future of clear aligner therapy looks promising; still, there is a need for additional advancement in materials and appliance design before 3D-printed aligners can fully satisfy clinical expectations and replace the thermoforming workflow.

Introduction:

Clear aligner therapy has become popular owing to its simplicity, comfort, almost invisible appearance, and removability for optimal hygiene maintenance (1).

Seeking orthodontic treatment is mostly because of the aesthetic influence of malocclusions (2). Clear aligners (CAs) are a viable alternative to fixed appliances for patients with mild-to-moderate malocclusion, but not for those with severe malocclusion (3). 3D-printed orthodontic appliances raise concerns regarding the physical properties and aging patterns of the materials (4), also some of the drawbacks of orthodontic aligners are their cost and the need for patient compliance (5).

Thermoplastic polyurethane and polyethylene terephthalate glycol (PET-G) are the primary materials used for the fabrication of orthodontic CA. Viscoelasticity is a property that these thermoplastic polymers exhibit; this means that they undergo deformation when subjected to stress, and then return to their initial form once the stress is removed. Well-known market brands use proprietary materials designed to meet standards, including optical stability that is unaffected by aging (5). 3D printing may create microporosities or material inconsistencies that enhance its ability to absorb pigments from food, beverages, and other external substances, resulting in a greater degree of color alteration over time in the oral cavity (6–8).

The manufacturing techniques for CAs include either thermoforming or 3D printing. Additive manufacturing, also known as 3D printing, constructs CAs layer by layer from a digital model (8–10). To apply the constant force necessary to reposition teeth effectively, these techniques use polyurethane-based materials, which are ideal because they combine transparency, strength, and flexibility (9–11).

Light-curing technology encompasses a group of three-dimensional (3D) printing methods that utilize photosensitive resins that undergo polymerization and structural formation when exposed to a light source. Stereolithography (SLA), digital light processing (DLP), and polyjet photopolymerization (PPP) are the three primary types of this technology (12).

The integration of three-dimensional printers and their associated materials with computer applications is facilitated through the use of digital technology. Currently, dental practitioners can program virtual tooth movement, utilize intraoral scanning technology, and directly print CA from a 3D printer while eliminating the need for traditional impressions or plaster models. This advancement significantly reduces the errors associated with thermoplastic workflows. The production of numerous aligners within a condensed timeframe through 3D printing significantly reduces labor requirements and minimizes waste and pollution (13). This method enhances both the sustainability and accuracy (14). A summary of aging effects on the properties of directly printed vs. thermoformed aligners based on the six studies is presented in Table 1.

This study provides an up-to-date review regarding the effect of aging on the morphological and optical properties of directly printed orthodontic aligners.

Advancements in 3D Printing for Clear Aligners

To solve the limits of conventional manufacturing techniques, recent efforts have been undertaken to directly 3D print CAs utilizing a biocompatible material, which requires less time and effort and produces fewer geometric errors as well (8); also, studies have investigated 3D-printed aligners' clinical viability, precision, and fit (8,15).

Tera Harz TC-85 (Graphy, Seoul, Korea), which has recently received approval from the European Commission (EC) and the Korea Food and Drug Administration (KFDA), represents a novel advancement in the field of 3D-printable biocompatible materials. While the precise chemical structure of the material remains undisclosed owing to patent limitations, the findings from the attenuated total reflectance-Fourier-transform infrared spectroscopic analysis indicate that the material is an aliphatic vinyl ester-urethane polymer, presumably cross-linked through methacrylate functionalization (4).

Throughout orthodontic treatment, patients using orthodontic appliances feel different degrees of pain and discomfort (16).

3D-printed materials are composed of cross-linked polymers, unlike traditional thermoplastic materials, which are made of non-cross-linked polymers used in thermoforming. The 3D-printed CAs made of TC-85 regularly exert a mild strain on teeth because of the material's viscoelastic and flexible characteristics. Additionally, it is anticipated that the force attenuation that is brought about by the recurrent insertion of transparent aligners will decrease, which will result in the consistency of the orthodontic force being maintained. The geometric stability of 3D-printed aligners at high temperatures, in addition to their shape memory qualities, are both advantages that can be utilized in clinical applications (17).

From Milling to Printing: The Shift in Dental Manufacturing Technologies

In subtractive manufacturing, a block of material is carved away to create the desired shape, whereas additive manufacturing is the exact opposite of this process (18). Currently, subtractive milling is the preferred computer-aided manufacturing process in the dental industry. With the increasing accuracy and versatility of additive manufacturing, its use in dentistry is likely to increase in the coming years. Additive manufacturing methods have proven effective across diverse industrial sectors and provide multiple advantages in the fabrication of dental structures compared to subtractive technology (12). The shear bond strength of the CAD/CAM milled cobalt-chromium alloy was comparable to that of the castable alloy. In metal-ceramic restorations, CAD/CAM milling with a cobalt-chromium alloy is a beneficial option compared with traditional castable alloys. Cobalt-chromium restorations may derive advantages from CAD/CAM manufacturing processes (19).

Degradation of Aligner Materials in the Oral Environment

A study found that polyurethane aligners experienced irreversible surface distortion in the oral environment and displayed a relatively high hardness (20). Despite the absence of molecular alterations in the material after use, subsequent retrieval analysis research revealed degradation in all mechanical parameters (21). Stress relaxation in aligners was shown to be improved at body temperature rather than room temperature (22).

Environmental degradation of CAs may result from the impact of cleansers and beverages that cause chemical wear on the aligners. Mouthwashes and peroxides do not influence the mechanical properties of thermoplastic materials. Toothpaste utilized for cleaning aligners contains abrasive particles that erode the aligner surface and alter its thickness. Consuming fluids while wearing aligners may reduce their thickness, as acidic or basic beverages can corrode the aligner's surface (23).

The patient’s compliance and behaviors should be considered when using CAs or aesthetic brackets, including ceramic and sapphire brackets and aesthetic archwires, as these orthodontic appliances are susceptible to staining from mouthwashes or the intake of chromogenic substances, which are important considerations for patients. So, the patients should follow the orthodontist's instructions regarding using cleaning agents and reduce their consumption of staining agents during the course of orthodontic treatment (24–27). For lowering plaque, bleeding and gingival inflammation; oral irrigation combined with tooth brushing is a better substitute for conventional dental floss (28).

The oral cavity contains substances, such as enzymes and mucinous proteins, with mechanisms for mastication, creating an environment where orthodontic appliances may experience stress, which may modify their structure, morphology, and physical properties. Furthermore, roughness can induce the release of several substances into the oral cavity (29).

Minor fractures of the CA could potentially be attributed to significant roughness. Possible causes of roughness in 3D-printed aligners include poor printing processes and excessive brushing of CAs. Multiple printing processes can increase the surface roughness of aligners owing to the varying circumstances during design, printing, or post-processing. For example, vertically printing aligners creates steps with multiple layers, whereas horizontal positioning creates a smoother surface with fewer layers. In addition, insufficient UV curing may result in a rough CA surface. Intraoral aging, which affects the morphological and optical properties of CAs, is another source of the high roughness in 3D-printed aligners. A foggy CA appearance could result from increased roughness, which prevents light from passing through, revealing CA presence in the oral cavity (29,30).

Morphological Properties of 3D-Printed Aligners

In particular concerning mechanical properties, the consistency of the material properties in printed aligners generated by different 3D printers has been closely examined, which may also influence the surface characterization of the materials (31).

Manufacturing technology, printing process, resin layer apposition, depth of cure, strength of interlayer bonding between printed layers, post-curing, oxygen-inhibited layer effect, condition, time, and direction could compromise the consistency and accuracy of the fabrication process and lead to end-products with different surface properties (32,33).

Intraoral aging reduces the mechanical quality and surface roughness of Invisalign® appliances. These characteristics deteriorated during the first week of clinical use and lacked temporal relevance (34). Intra-oral exposure and function at all levels significantly and holistically changed the surface roughness characteristics of aligners made in-house. If any exists, the link between clinical efficiency and safety of orthodontic treatment using such appliances is unknown (29).

Surface irregularities and heterogeneity may be exacerbated by enzymatic action, pH shifts, acidic beverage consumption, chewing motion, and tooth brushing, leading to an increase in surface roughness (20).

3D-printed polyurethane materials may exhibit greater staining than those produced by thermoforming because of variations in the morphological properties resulting from the two manufacturing techniques. In particular, parts made by 3D printing often have rougher and more porous surfaces, facilitating the entrapment of staining agents, whereas components made by thermoforming often have denser and smoother structures, which are less susceptible to staining (35).

The addition of 3D-printing materials may affect stain resistance, suggesting that 3D-printed polyurethane formulations may differ from thermoformed formulations. Moreover, the thermal history and consequent microstructure linked to various manufacturing methods may influence the stain resistance of materials. 3D-printed materials may exhibit an increased number of reactive sites for stain adsorption, owing to their fast-cooling times and incremental production. Additionally, the morphological properties may change owing to chemical exposure during 3D printing, affecting the stain interaction (36–38).

Mechanical strain may induce material shrinkage and expansion, leading to variations in tooth thickness, which in turn can contribute to morphological inconsistencies that hinder effective orthodontic tooth movement (39).

Plaque Accumulation on the Surface of Aligners

According to Tektas et al. (40), metal orthodontic brackets, aligner materials, and enamel are equally susceptible to the initial adhesion of bacteria and the production of biofilms by oxygen-requiring and oxygen-free oral microorganisms. The layout, featuring grooves and ridges, facilitates microbial attachment to the aligners. Moreover, the surfaces of new CAs generally display characteristics such as scratches, microabrasions, and bumps, which are the primary loci where microbes attach and grow (40).

Furthermore, researchers have provided evidence of physical and chemical alterations in aligners. Two weeks later, the aligners showed microcracks, abraded areas, and delaminated sections vulnerable to bacterial adhesion and spread. Moreover, localized deposits and a decrease in transparency were noted (41).

Optical Properties of 3D-Printed Aligners

Increased surface roughness combined with inadequate oral hygiene could compromise the absorption of saliva, water, and other fluids, resulting in the discoloration of CAs during intraoral insertion (42–44). Lira et al. noticed that after two weeks of use in the mouth, the surface became rougher as depicted in Figure 1, which caused the transparency to decrease and the color of the aligner to become more noticeable as shown in Figure 2 (43).

Orthodontic patients need specific oral hygiene practices to prevent different plaque-related problems (45). Individuals undergoing treatment with CAs showed improved periodontal health, and minimal white spot lesions emerged during therapy (46).

The properties of 3D-printing materials depend on resin composition and 3D-printing technology. Materials with a higher degree of crosslinking have better strength and resistance to aging, but low ductility. The liquid crystal display (LCD) 3D printing technology generates appliances characterized by increased surface roughness, resulting in reduced transparency and compromised color stability.

The mechanical, surface, and optical characteristics of 3D-printing materials demand further research to obtain clinical acceptance for orthodontic retainers (47). Analyzing thermoforming disks indicates less optical property deterioration across Carbon L1, Prodways LD20, and RapidShape D100+ 3D printers (48).

To achieve optimal clarity, CA materials must possess remarkable light transmission properties, preferably permitting over 80% visible light penetration. The preferred materials for CAs are amorphous thermoplastic polymers, attributed to their superior translucency relative to less aesthetically pleasing, opaque crystalline polymers. Polymers, including polyurethane, polyester, and polycarbonate, are particularly valued owing to their advantageous optical properties. High transparency and visual appeal of CAs are essential for their success (49).

CAs featuring a PETG outer layer exhibit greater resistance to stains and chemical modifications than those constructed from polyurethane. Moreover, 3D-printed polyurethane aligners exhibit a greater susceptibility to staining than thermoformed alternatives. This makes PETG-layered aligners a more reliable option for maintaining aesthetic integrity (50).

Conclusion

Aging adversely affects surface roughness and optical properties of 3D-printed orthodontic aligners in comparison to commonly used thermoplastic materials. Cleaning techniques used affected variations in translucency and thickness of the 3D-printed aligners. 3D-printing resins fail to satisfy the clinical standards for surface roughness and optical characteristics required for the production of orthodontic clear retainers after artificial aging. The future of CA therapy looks promising; still, there is a need for additional advancement in materials and appliance design before 3D-printed aligners can fully satisfy clinical expectations and replace the thermoforming workflow. Further trials are needed to offer the 3D-printed aligners with the least adverse effects on their properties during orthodontic treatment.

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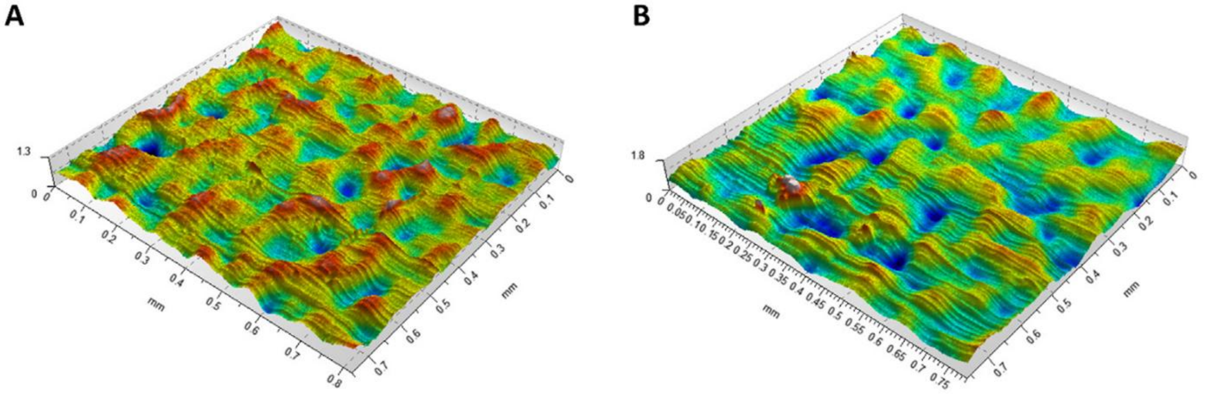

Figure (1): Three-dimensional image of the morphologic surface of orthodontic aligners: A, Reference group; B, In-vivo aged group. Red signifies peaks; blue denotes valleys (43).

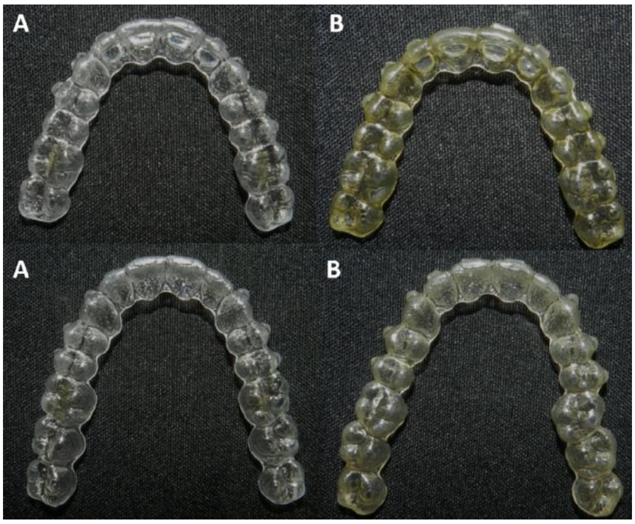

Figure (2): Images of orthodontic aligners: A: Prior to exposure to the intraoral environment; B: Following two weeks of exposure to the intraoral environment (43).

Table (1): Studies on the properties of directly printed vs. thermoformed aligners after aging.

No.	**Researchers**	**Sample size**	**Study type**	**Materials**	**Findings**
1.	Sayahpour et al., 2024 (14)	60	In vitro	Tera Harz TC-85 DAC resin (Graphy, Korea), Duran and thermoforming foils (Scheu Dental, Iserlohn, Germany), and polyurethane-based polymer Invisalign (Align Technology, Inc., CA, USA).	In terms of mechanical attributes, Duran has shown superiority to both DP and INV. Stiffness and force decay characteristics were greatly increased in DP aligners, as demonstrated by the dramatically elevated RIT and EIT values.
2.	Neoh et al., 2025 (47)	NA	In vitro	Duran (Scheu Dental GmbH, Iserlohn, Germany) and Zendura (Bay Materials LLC, Fremont, Calif), and 3D printing resins (Dental LT Clear V2 (Formlabs Inc., Somerville, Mass) and OrthoFlex (Nextdent BV, Soesterberg, The Netherlands).	OrthoFlex, 3D printing resins have rather poor surface roughness, transparency, and color stability. Compared to thermoplastic materials, the evaluated 3D-printing resins show less ductility and more brittleness. The 3D-printing resins fail to satisfy the clinical standards for surface roughness and optical characteristics required for the production of orthodontic clear retainers.
3.	Koletsi et al., 2023 (29)	48	In vitro study following intra-oral material aging	Tera Harz TC-85 DAC resin (Graphy, Korea), Invisalign® (Align Technology, San Jose, CA, USA) appliances (material: SmartTrack™).	Significant changes in the surface roughness properties of 'in-house' produced aligners across all levels came from intraoral exposure and function. The relationship between clinical efficacy and safety in orthodontic therapy with these appliances has to be determined.

4.	Kuntz et al., 2024 (5)	80	In vitro	Angel® (Master Control S®) (AngelAligner®, China), Accusmile® (PET-G) (Forestadent Bernhard Foerster GmbH®, Pforzheim, Germany), Suresmile® (EssixTM ACE) (Dentsply Sirona Inc®, Charlotte, North Carolina, USA), Invisalign® (SmartTrack) (Align Technology, Inc., CA, USA), and GRAPHY® (Tera Harz TC-85) (Graphy, Korea).	Comparatively to substitutes, GRAPHY® aligners show less strength and more variation. Aging had no effect on the mechanical characteristics of Accusmile®, GRAPHY®, Invisalign®, Suresmile® or any other. Aging alters the surface conditions.
5.	Eslami et al., 2024 (42)	136	In vivo	Tera Harz TC-85 DAC resin (Graphy, Korea), Invisalign® (Align Technology, San Jose, CA, USA) (material: SmartTrack™).	One week of intraoral use significantly raised DP aligners' surface roughness and porosity, so perhaps increasing bacterial adhesion and biofilm development on these aligners. Following intraoral exposure, the surface roughness and porosity of the Invisalign aligners were markedly minimized.

6.	Park et al., 2023 (13)	40	In vitro	polyethylene terephthalate glycol, copolyester-elastomer combination, and 3D-printed TC-85.	Following fabrication, a decrease in thickness was observed in the thermoformed groups, whereas the 3D-printed groups exhibited an increase in thickness. The thermoformed copolyester-elastomer combination group exhibited a significantly smaller gap width compared to the other groups ($p < 0.01$). Thermoformed and 3D-printed aligners showed rather different thickness and ideal fit across various tooth types and positions. Cleaning techniques used affected variations in translucency and thickness of the 3D-printed aligners.

EIT, indentation

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