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Original Article

Evolution of Aligner Materials

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ABSTRACT

This review explores the evolution and development of aligner materials used in orthodontic clear aligner therapy. Beginning with early innovations such as Kesling's tooth positioners in 1945 and progressing through advancements like thermoformed plastic appliances, invisible retainers, and silicone-based materials, the article traces the technological milestones that have shaped modern aligner systems. Emphasis is placed on the materials' physical properties—such as flexibility, strength, and transparency—and their impact on clinical performance, comfort, and aesthetic appeal. The review also discusses recent advancements in polymer science and 3D printing technologies, which have enabled the creation of customized aligners with enhanced biomechanical efficiency. By examining comparative studies and material-specific performance metrics, this paper provides a comprehensive overview of the state of aligner materials and identifies emerging trends and challenges in the field.

Keywords: Aligner material, Invisalign, Thermoplastic materials, Polyethylene– Copolyester, Polypropylene, Ethylene vinyl acetate, Polyurethane

INTRODUCTION

Clear Aligners is an orthodontic technique that uses a series of computer-generated custom plastic aligners to guide the teeth into proper alignment. The use of clear aligner is a growing part of the orthodontic market and as a result many new products have become available.[1] The development of clear aligner technology in orthodontics has been characterized by several noteworthy breakthroughs. The adventure started in 1945 when H.D. Kesling developed the idea of tooth positioners, the first tools for small tooth movements. Nahoum invented thermoformed plastic appliances in 1960, providing a more comfortable and versatile dental repair option. By creating the invisible retainer in 1971, Pontiz improved upon these developments even further and offered a covert way to keep teeth in alignment.[2] The 1980s witnessed another pivotal shift as silicon replaced plastic in retainer design, an improvement led by McNamara to enhance the durability and effectiveness of these devices. In 1993, Hilard and Sheridan introduced a progressive alignment approach using clear Essix appliances, laying the groundwork for modern clear aligner systems. The most transformative breakthrough came in 1997 when Zia Chishti and Kelsey Wirth invented the world's first comprehensive clear aligner system, revolutionizing orthodontic treatment by making it more efficient, customizable, and aesthetically pleasing.[1] This innovation marked the beginning of a new era in orthodontics, making clear aligners a popular and accessible choice for patients worldwide also known as Invisalign, it involved a series of removable clear plastic aligners aimed at seeking discrete orthodontic treatment These are transparent, removable and moldable braces.[2] Instead of one pair of braces being constantly adjusted, a series of braces are worn in succession, each created by a computer they are worn for at least 22 hours a day for 3 weeks before changing to the next one.[3] The length of treatment depends upon the severity of each case that is 3 weeks to 6 months. Clear aligners have become a popular choice for orthodontic treatment, particularly in cases of mild to moderate crowding or spacing. They are effective for the intrusion and extrusion of incisors, posterior dental expansion, deep bite correction, and management of unilateral open bites. Additionally, aligners can tip molars distally and assist in rotating incisors and canines with the help of bonded

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attachments. More complex movements, such as premolar extraction space closure, molar relationship correction, and comprehensive bite corrections, often require the use of attachments and specially designed aligners.[3] The advantages of clear aligners are numerous. They are nearly invisible, thin, and do not interfere with speech. Being removable, they allow for easier oral hygiene. Clear aligners are particularly appealing to adults seeking a discreet and comfortable alternative to traditional braces, with faster results and a customized digital treatment plan. However, challenges include initial speech difficulties, discomfort with aligner changes, impression inaccuracies, the risk of losing aligners, and the need for strong patient compliance. Costs can also be relatively high

Different Generations of Aligners[4]

- **First Generation**

Based solely on aligner; no auxiliary elements

- **Second Generation**

Use of attachments like composite buttons and intermaxillary elastics

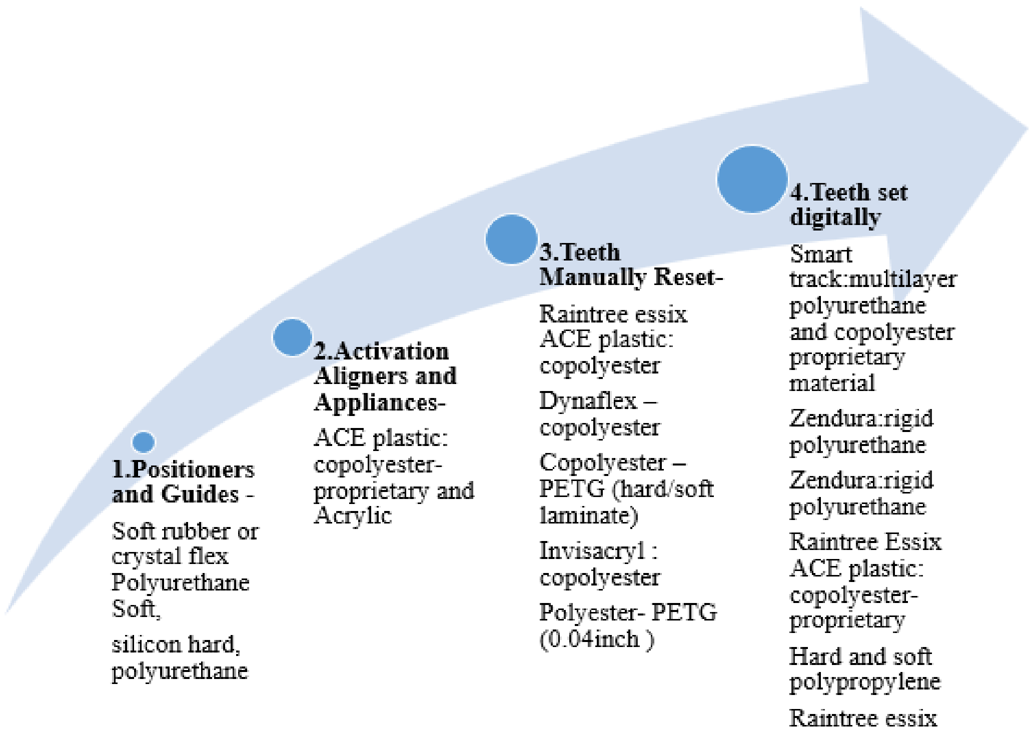
- **Third Generation**

Attachments placed via software to improve tooth movement control[4] Analog CAT involves a physical model that is modified either by resetting the teeth or creating divots and voids in the model prior to vacuum-forming Digital CAT starts with a 3-D scan of the dental arches, an impression, or a plaster model.[5]

THERMOPLASTIC MATERIALS

- Poly Methyl Methacrylate
- Polycarbonate
- Polyethylene –Copolyester
- polyethylene terephthalate
- polyethylene terephthalate glycol modified
- Polypropylene
- Ethylene vinyl acetate
- Polyurethane

There has been a rapid evolution in the clear aligner therapy and their materials starting from kesling's retainer to Invisalign. There are a number of thermoplastic materials used for aligner fabrication based on their evolution and also the various companies. Thermoplastic material is a plastic polymer that becomes pliable or moldable at a certain elevated temperature and solidifies on cooling.



Acrylic

It is a transparent thermoplastic material often used in sheet form as alternative to glass It is transparent to light in the visible and UV range wavelength 250nm. It is a copolymer of methyl methacrylate and butyl methacrylate which forms the PMMA. With a density of 1.19 gm/cm³, the substance absorbs water at a rate of 0.3%. It has a flexural strength between 82 and 119 MPa and a tensile strength of 60 MPa. Its hardness number ranges from 18 to 20 KHN, and its compressive strength ranges from 75 to 131 MPa. The thermal conductivity is 3.9 and the coefficient of thermal expansion is measured between 5- and 9-degrees Fahrenheit. Furthermore, the refractive index falls between 1.48 and 1.50, and the modulus of elasticity is 2.4 GPa.[6] This substance has several advantages, such as outstanding chemical stability and anti-aging qualities since it doesn't discolor when exposed to UV radiation. It is durable, simple to handle, resistant to wear, and easily cleaned and sanitized. It is also very robust and physiologically safe, which makes it perfect for a variety of uses. There are a few drawbacks to take into account, though. It is prone to stress cracking and has low solvent resistance. In addition to being flammable, the material is weaker than alternatives. Additionally, there are no flexible acrylic grades available, and it is prone to deformation.[6]

Polycarbonate

These are a group of thermoplastic polymers containing carbonate groups in their chemical structure. It is produced by the reaction of bisphenol A and phosgene. With a density of 1.22 gm/cm³, the material absorbs water extremely little—just 0.1%. Its flexural strength is between 82 and 119 MPa, while its tensile strength is between 55 and 75 MPa. About 80 MPa is its compressive strength. At 70 KHN, the hardness is measured. Its thermal conductivity ranges from 0.19 to 0.22 degrees Fahrenheit, while its coefficient of thermal expansion is between 5 and 9 degrees. Furthermore, the material's refractive index ranges from 1.584 to 1.586, and its modulus of elasticity is between 2.0 and 2.4 GPa. It has high impact resistance and low scratch resistance. compared to pmma, it is stronger and can withstand extreme temperatures. It is highly transparent in visible light.it can undergo large plastic deformations without cracking or breaking The material offers several advantages: it is durable, moldable, and lightweight, making it highly versatile. It is also flame resistant and shatterproof, providing added safety benefits. Additionally, it delivers superior esthetics while maintaining a reasonable material cost. Its flexibility and better adaptability further enhance its practical applications. However, there are some disadvantages to consider. The material requires high processing temperatures and can degrade with extended processing times. It may also exhibit aromatic sensitivity and has a tendency to yellow over time.[8]

Polyethylene

- Also known as polyethene or polymethylene.
- It is a mixture of similar polymers of ethylene with various values of n

Mechanically, the material exhibits low strength, hardness, and rigidity, but it offers high ductility, excellent impact strength, and low friction properties. Thermally, it has a low melting point, ranging between 105 to 115 degrees Celsius, and a thermal conductivity of 0.4. Chemically, the material is partially crystalline and provides excellent chemical resistance. In terms of electrical properties, it acts as a good electrical insulator and offers strong resistance to electrical treeing. Optically, the material can vary between transparent, translucent, or opaque, although its transparency is reduced due to the presence of crystallites. [9] Electric treeing: pre-electric breakdown phenomenon in solid insulation due to partial discharges and progresses through the stressed dielectric insulation in the path resembling the branches of a tree Despite its useful properties, the material presents several notable disadvantages. It possesses relatively low strength and stiffness, limiting its performance under mechanical stress. The material is also highly flammable, posing potential safety risks in certain applications. Its poor resistance to ultraviolet (UV) radiation leads to accelerated degradation when exposed to sunlight over time. Furthermore, it is vulnerable to environmental stress cracking, which can compromise its structural integrity under harsh conditions. The material exhibits high gas permeability, making it less suitable for applications requiring effective gas barriers. Lastly, its environmental impact is a significant concern, as it contributes to pollution and raises sustainability issues.

Copolyester

Copolyesters are derived by modifying traditional polyesters, which are typically formed from a reaction between diacids and diols. These modifications involve incorporating alternative monomers, such as isophthalic acid (IPA) or cyclohexane dimethanol (CHDM), into the structure of standard polyethylene terephthalate (PET). Despite these structural changes, copolyesters continue to exhibit desirable properties like high strength, optical clarity, and stable mechanical performance. Additionally, they offer enhanced versatility and flexibility, making them suitable for a wide range of applications. [9]

Polyethylene Terephthalate

- PET is the most common thermoplastic polymer resin of the polyester family.
- It consists of polymerized units of monomer ethylene terephthalate.
- It may exist both as an amorphous or a semi-crystalline polymer.

The material has a density of 1.38 gm/cm³ and a water absorption rate of 0.16%. It exhibits a tensile strength ranging from 55 to 75 MPa and a flexural strength of 221 MPa. The compressive strength of the material is 80 MPa. It has a coefficient of thermal expansion of 7 degrees Fahrenheit and a thermal conductivity of 0.24. The modulus of elasticity falls between 2800 and 3100 MPa, indicating good stiffness and strength. Additionally, the material's refractive index ranges from 1.57 to 1.58. The material offers several advantages, including being readily available and inexpensive, making it a practical choice for many applications. It is virtually shatterproof and provides excellent chemical resistance, ensuring durability in harsh environments. Additionally, it is highly transparent and features a high strength-to-weight ratio, enhancing both its performance and versatility. However, the material also has some disadvantages. It is susceptible to oxidation, can be affected by high temperatures, and is not biodegradable, raising environmental concerns regarding its long-term disposal.[9]

PET – Glycol Modified

The physical and mechanical characteristics of polyethylene terephthalate (PET) can be adjusted through copolymerization with various diols, resulting in what is known as polyethylene terephthalate glycol-modified, or PETG. This modification typically involves replacing ethylene glycol with longer-chain glycols in varying proportions. The presence of glycol in the polymer structure imparts several beneficial properties. It enhances the flexibility of the material, making it more impact-resistant compared to standard PET. Additionally, glycol modification eliminates the hazing effect that can occur during thermal processing and prevents unwanted crystallization, which would otherwise make PET more brittle. These improvements make PETG a more durable and visually clear alternative for a variety of applications.

Polypropylene [9]

- Polypropylene or polypropene is a thermoplastic polymer produced via chain-growth polymerization from the monomer propylene.
- It belongs to the group of polyolefins and is partially crystalline and non-polar.

The material possesses a range of important properties. Physically, it is a stiffer material with greater resistance to creep. Mechanically, it has a density between 0.89 and 0.92 gm/cm³ and a modulus of elasticity ranging from 1300 to 1800 MPa, along with good resistance to fatigue. Thermally, it exhibits a large thermal expansion—though less than polyethylene—and a thermal conductivity between 0.27 and 2.5. Chemically, the material is resistant to fats and nearly all organic solvents, except strong oxidants at room temperature. Optically, it is often opaque but can be colored with pigments or made translucent when uncolored. The material offers several advantages, including high processability, high impact resistance, high stiffness, excellent flexural strength, good fatigue and chemical resistance, and low cost. However, it also has certain disadvantages: it degrades under UV light, is flammable, is susceptible to attack by chlorinated solvents and aromatics, is difficult to bond, has relatively poor strength, and shows low impact resistance at low temperatures.

Ethylene Vinyl Acetate [10]

Poly (ethylene vinyl acetate), commonly referred to as EVA, is a copolymer composed of ethylene and vinyl acetate. The properties and applications of EVA vary depending on the proportion of vinyl acetate present in the composition. Based on this variation, EVA is generally classified into three main types: vinyl acetate-modified polyethylene, which has a lower vinyl acetate content and behaves similarly to polyethylene; thermoplastic ethylene vinyl acetate, which has a moderate amount of vinyl acetate and exhibits rubber-like flexibility with thermoplastic processability; and ethylene vinyl acetate rubber, which contains a higher proportion of vinyl acetate, giving it more elastomeric characteristics suitable for rubber-like applications.

Vinyl Acetate Modified

When the vinyl acetate (VA) content in ethylene-vinyl acetate (EVA) copolymers is up to 4%, the material behaves similarly to low-density polyethylene and can be processed as a thermoplastic polymer. This low VA content enhances certain characteristics of the material, such as increasing its gloss, softness, and flexibility. Additionally, EVA in this composition range is regarded as non-toxic, making it suitable for a wide range of applications, including those requiring safety and environmental compatibility.

Thermoplastic Eva

Ethylene-vinyl acetate (EVA) with a medium vinyl acetate (VA) content, typically between 4% and 30%, exhibits a unique balance of properties. Although it is not vulcanized, this form of EVA displays certain rubber-like characteristics, offering flexibility and resilience. It is known for its toughness and effective performance at low temperatures, making it suitable for applications requiring durability under thermal stress. Notably, EVA containing around 11% vinyl acetate is widely used in the production of hot melt adhesives due to its strong bonding ability and ease of application.

Eva Rubber

Ethylene-vinyl acetate (EVA) containing a high vinyl acetate (VA) content of 60% or more represents the most flexible and resilient form of the copolymer. This type of EVA is characterized by its excellent stress crack resistance and superior toughness, along with enhanced transparency. It also possesses a distinct vinegar-like odor due to the high concentration of vinyl acetate. Additionally, this variant offers strong resistance to ultraviolet (UV) radiation, making it suitable for applications that require durability and performance under prolonged sun exposure.[10]

Polyurethane

Polyurethane is a polymer formed through step-reaction polymerization, consisting of organic units connected by urethane linkages. Depending on its formulation, it can exist as either a thermoplastic or a thermosetting polymer, offering versatility in various applications. As it is synthesized from two different types of monomers that alternate along the chain, it is classified as an alternating polymer.[8]

MANUFACTURE

- Basic intermediate prepared in the form of polyether or polyester
- This intermediate reacts with an aromatic di isocyanate to yield a prepolymer
- This elastomer is vulcanized through isocyanate groups by reaction with alcohols or glycols

Types

- flexible
- rigid
- Case
- Thermoplastic
- Water borne
- Binders
- Reaction injection molding

Properties

The material has a density of 1.12 gm/cm³ and a water absorption rate of less than 0.5%, indicating low moisture uptake. It exhibits a tensile strength of 18 MPa and a flexural strength of 30 MPa. The compressive strength ranges between 90 and 250 MPa, suggesting good performance under compressive loads. The coefficient of thermal expansion is 57.6, while the thermal conductivity falls between 0.22 and 0.28, reflecting moderate thermal properties. Additionally, the material has a high modulus of elasticity, ranging from 8000 to 11000 MPa, indicating significant stiffness. The refractive index varies from 1.52 to 1.57, providing moderate optical clarity.[11] Polyurethane offers several advantages that make it valuable across a range of applications. It is known for its high resistance to abrasion and impact, along with excellent elastic memory and resilience. The material can be easily colored and is available in a wide range of hardness levels, making it adaptable to different requirements. Additionally, it has a variable coefficient of expansion, which enhances its versatility. However, there are also notable drawbacks. Polyurethane tends to have a shorter lifespan and may emit unpleasant odors and fumes during use or processing. Exposure to the material can cause health concerns such as allergic reactions, skin rashes, or even more severe effects like loss of consciousness. Furthermore, the processing of polyurethane involves toxic substances, which raises safety and environmental concerns.[11]

Clear Aligner Therapy

- Several companies around the globe are manufacturing aligners, with the number increasing every year.

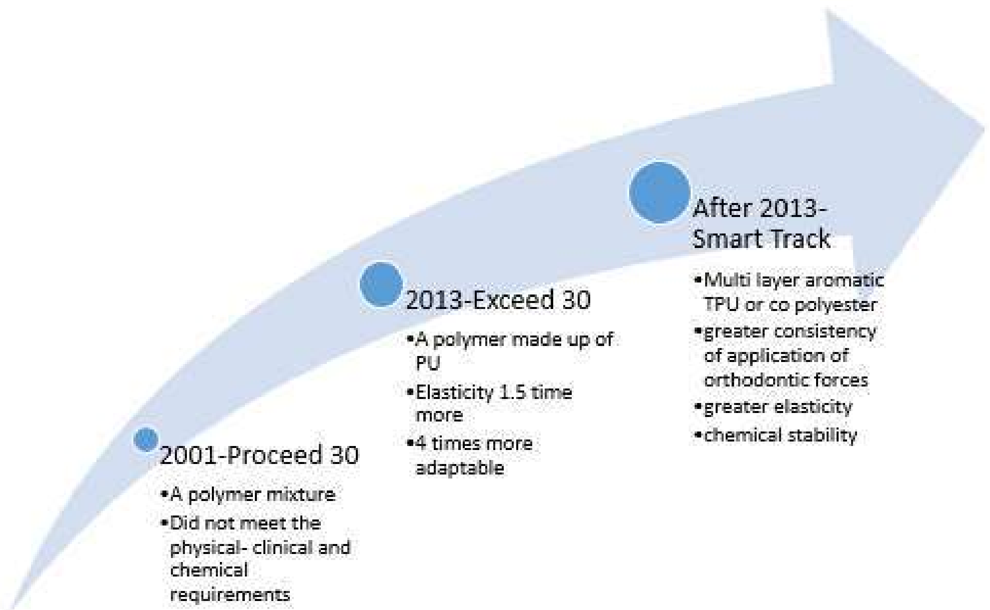
Some of them are as follows: -

Invisalign, Clear correct, Dentsply Sirona, Dynaflex, Scheu-Dental, Smile direct club, Snap correct, k-line Europe, Candid co, Exceed technologies, Spark aligners

Invisalign

The Invisalign system is a nearly invisible orthodontic treatment that utilizes a series of custom-made, removable aligners to gradually shift teeth into their desired positions.[14] Introduced in 1997 by Align Technology, the system has undergone several advancements over the years. In 2005, the company launched Invisalign Express, a shorter treatment option for minor corrections. By 2008, the system had expanded its capabilities to address more complex tooth movements. In 2009, SmartForce attachments were introduced to enhance the effectiveness of the aligners. The integration of the iTero scanner in 2011 further improved treatment precision by allowing digital impressions. In 2016, the protocol evolved to support weekly aligner changes, significantly reducing overall treatment time. [15]

Smarttrack Material



SmartTrack material, used in advanced orthodontic aligners, is designed to provide a gentle and consistent force throughout the duration of wear, enhancing patient comfort and treatment efficiency. It is free from substances such as bisphenol A, latex, and plasticizers, making it a safer option for sensitive users. This material is known for its excellent elasticity and snug fit, contributing to more accurate tooth movement. Additionally, SmartTrack offers good translucency and flexibility, which allows for better adaptability to individual dental structures. Its chemical stability ensures durability, while its proven clinical effectiveness supports improved outcomes in orthodontic treatments. The Invisalign system offers several advantages, primarily due to its use of SmartTrack material, which enhances comfort and treatment efficiency. It also utilizes intraoral scans for more precise and customized aligner fitting. To help ensure proper usage, each aligner is equipped with a blue compliance indicator, allowing patients to track their wear time. Additionally, every aligner is carefully trimmed to match the individual gum line of each patient, improving both comfort and aesthetics. These features contribute to a more effective and personalized orthodontic treatment experience. [15]

CONCLUSION

The properties to be prioritized before aligner fabrication are modulus of elasticity, stress relaxation, tear strength and water absorption rate. Other properties like thickness, density, thermal and chemical properties also should be considered. The choice of material is important because plastics for aligners are subject to stress relaxation and water absorption that may affect their ability to deliver tooth moving forces over time. So based on this, the thermoplastic materials like PETG, Polypropylene and TPU offer superior properties in comparison to the others.

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