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## REVIEW ARTICLE

# Materials in digital dentistry—A review

Taiseer A. Sulaiman BDS, PhD 

Division Director of Operative Dentistry and Biomaterials, Department of Restorative Sciences, UNC Adams School of Dentistry, Chapel Hill, North Carolina

**Correspondence**

Taiseer A. Sulaiman, Division Director of Operative Dentistry and Biomaterials, Department of Restorative Sciences, UNC Adams School of Dentistry, 4604 Koury Oral Health Sciences Building, CB 7450, Chapel Hill, NC 27599.

Email: sulaiman@unc.edu

**Abstract**

**Objective:** To review materials available in computer-aided design/computer-aided manufacturing (CAD/CAM), their various properties and accuracy are compared to conventional materials/methods when available.

**Overview:** CAD/CAM in dentistry is constantly growing and becoming a user- and patient-friendly technology and service using intraoral scanners and laboratory/ chairside milling units to manufacture dental restorations and appliances from multiple materials including wax, metals, composite resins, and ceramics. Properties of these materials may vary when compared to restorations prepared from conventional and additive manufacturing methods. Understanding the differences in these properties is important for material and fabrication method selection. Additive manufacturing is becoming an alternative to subtractive manufacturing in many applications. However, chemical composition, mechanical and physical properties of these materials are still lacking. 3D printed materials require a considerable amount of research and time to prove their clinical efficacy.

**Conclusion:** The current developments in, and possibilities of, CAD/CAM technology is exciting and is transforming restorative dentistry. With all this excitement, it is crucially important to ensure that proper testing and evaluation of the various materials are warranted before making definite claims and decisions to replace conventionally prepared materials.

**Clinical Significance:** CAD/CAM materials are versatile and emerging as the material of choice for many restorations and appliances. For recently introduced CAD/CAM materials, it is important to ensure that proper clinical- and research-based evidence confirming the success and durability of these materials are available before recommending them in patient care.

**KEYWORDS**

additive manufacturing, CAD/CAM dentistry, dental materials, digital dentistry, subtractive manufacturing

## 1 | INTRODUCTION

Computer-aided design/computer-aided manufacturing (CAD/CAM) has been used for decades in industry and has increased in popularity over the past years in dentistry from making impressions, casts, and provisional fabrication to the final restorations.<sup>1–3</sup> Dental CAD/CAM systems consist of a scanner, software that processes the scanned

data, and a fabrication system that transforms the data into an actual restoration, denture, or appliance. This “digital workflow” records both dentitions allowing the clinician to review and evaluate the tooth preparation and design a restoration that fulfills the intended treatment plan. A digital file can be uploaded to a cloud server for quick communication with the technician allowing any adjustment to be made before continuing to the next step. The process is usually time

efficient and eliminates the need for impression materials, and in most cases, allowing the delivery of the final product on the same day and in the same appointment.

There are several scanning systems available in the market today. Some require the use of an oxide powder to enhance the quality of the scan. Scanning is processed either relying on a series of static images or a stream of video images to capture the geometry of tooth preparation. The designing software is proprietary to each system allowing the clinician/technician to design the restoration/appliance and in relation to the opposing dentition. The processed data is then manufactured either chairside, in a laboratory, or in a centralized production center.<sup>4</sup> Manufacturing process can be either subtractive or additive.

It is crucially important for the restorative team to understand the spectrum of CAD/CAM materials that are available in order to ensure optimal treatment outcomes for the patients. This review will focus on the materials utilizing CAD/CAM technologies, the properties of these materials, and accuracy compared to conventional methods and materials used in restorative dentistry. Materials produced by subtractive manufacturing (SM) will first be reviewed, followed by the materials produced by additive manufacturing (AM).

## 2 | SUBTRACTIVE MANUFACTURING

SM usually involves milling the designed volumetric shape from a presintered or sintered material using a milling machine that performs either in a wet or dry condition, that moves in defined paths, referred to as 3-, 4-, 5-axes milling systems.<sup>5</sup> The milling systems are either laboratory or chairside milling systems. A digital file (stl, an abbreviation of "stereolithography") is used to digitally design the restoration or appliance, the final design is sent to the milling system for manufacturing. Recent millable materials include wax, poly(methyl methacrylate) (PMMA), composite resins, high-performance polymers, metals, and ceramics which include: glass-ceramics, polymers reinforced with ceramic particles commonly known as (resin-based ceramics), ceramics infiltrated with a polymer also known as (hybrid ceramics), and polycrystalline ceramics.

### 2.1 | Wax

Mainly composed of acrylate polymers, wax patterns for various restorative procedures can now be digitally designed and milled making them time- and cost-effective. Traditional waxing is both skill-demanding and time-consuming. The final wax pattern is either processed through metal casting or pressed with a ceramic. Multiple manufacturers provide millable wax blocks, for example (VITA CAD-Wax Blocks VITA North America, Yorba Linda, California). Marginal fit accuracy of restorations fabricated by conventional and CAD/CAM wax-up methods have been compared to conventional wax methods and wax patterns fabricated by additive technology. This will be presented later in the article.

### 2.2 | Poly(methyl methacrylate)

PMMA is a synthetic polymer produced from polymerization of methyl methacrylate. PMMA is a millable block that is used for long term single crowns and fixed partial dentures. A recent study compared the mechanical properties and marginal fit of PMMA inlays to glass-ceramic inlays, both with similar outcomes.<sup>6</sup> Increased interest in PMMA restorations encouraged the development of PMMA blocks with enhanced optical and physical properties, (eg, Telio CAD, Ivoclar Vivadent, Shaan, Liechtenstein and VITA CAD-Temp MultiColor Blocks, VITA Zahnfabrik, Bad Sackingen, Germany). Processed PMMA restorations are easily polished to achieve enhanced esthetics.

Recently, CAD/CAM PMMA has been the material of choice for milling dentures that are colored and polished similar to conventional dentures (eg, IvoBase CAD, Ivoclar Vivadent), followed by milling of teeth from double cross-linked resin material that are bonded to the denture base (eg, SR Vivodent CAD, Ivoclar Vivadent). Strength and surface roughness properties of CAD/CAM PMMA dentures have been compared to conventional heat cured PMMA CAD/CAM PMMA displayed superior strength and surface characteristics, indicating a more durable denture.<sup>7-9</sup> Different brands of CAD/CAM PMMA have inherent variable properties. Fitting of CAD/CAM dentures were superior to conventional dentures, resulting in enhanced retention and lower traumatic ulcer-frequency with CAD/CAM dentures.<sup>10</sup> Composition, properties, and preparation requirement can be found in Table 1.<sup>11-13</sup>

### 2.3 | Composite resins

Composite resins are composed of inorganic or organic fillers embedded in an organic resin matrix with initiators, stabilizers, and pigments, whereas direct composite resins are applied, modeled, and polymerized intraorally; indirect composite resins from prepolymerized millable blocks are designed, milled, and polymerized extraorally overcoming some shortcomings of direct composites such as polymerizations shrinkage, leachable monomers, and enhanced mechanical properties. Millable composite resins require minimal postprocessing steps, polishing, and possibly adding photopolymerizable stains for characterization to produce restorations such as veneers, inlays, onlays, and crowns. Reported strength and other properties have been compared to ceramic blocks with no consensus on what material is superior.<sup>14,15</sup> Further studies, preferably clinical trials, are required to determine the material of choice for the mentioned applications. Examples of CAD/CAM composite resins include Paradigm MZ100, 3M ESPE (St. Paul, Minnesota) and BRILLIANT Crios (Coltene, Altstätten, Switzerland). Composition, properties, and preparation requirements can be found in Table 2.<sup>11,16-20</sup>

### 2.4 | Reinforced (high-performance) polymers

High-performance polymers have been a desirable option for many clinicians considering their mechanical, physical, and biocompatible properties. Polyetheretherketone (PEEK), thermoplastic polyaryletherketone (Pekkton),

**TABLE 1** CAD/CAM poly(methyl methacrylate) (PMMA) composition, properties, and preparation requirement

Properties	Telio CAD	VITA CAD-Temp	artBloc Temp	Dentokeep
Composition	99.5% PMMA polymer	PMMA, inorganic microfillers	PMMA, organic fillers	PEEK (80%) and TiO <sub>2</sub> (20%)
Flexural strength (MPa)	135 <sup>a</sup>	≥80 <sup>a</sup>	93 <sup>a</sup>	NP
Modulus of elasticity (GPa)	3.10	2.80 <sup>a</sup>	2.68 <sup>a</sup>	3.43 ± 0.29 <sup>11</sup>
Water sorption (μg/mm <sup>3</sup> )	23.20 ± 0.10 <sup>12</sup>	NP	NP	~2.20
Fracture load (Newton)	~900 <sup>a</sup>	~500 <sup>a</sup>	~700 <sup>a</sup>	NP
Vickers hardness (VH)	NP	NP	NP	27.74 <sup>11</sup>
Wear (two-body) (mm <sup>3</sup> )	~115 <sup>13</sup>	~105 <sup>13</sup>	NP	NP
Minimum wall thickness occlusal	1.50 mm	1.50 mm	1.00 mm	NP
Minimum wall thickness circumferential	0.80 mm	0.80 mm	1.00 mm	NP

Abbreviations: NP, not provided; PEEK, polyetheretherketone.

<sup>a</sup>Data from the manufacturer.

and fiber reinforced composite blocks (eg, Trinia, Shofu, Japan) have been used to mill removable partial denture frameworks and fixed restorations including crowns, three-unit bridges, custom implant abutments, implant-supported superstructures, and telescopic copings. Postprocessing of these materials is mechanically stable, more easily milled than metals, and are therefore friendlier to the milling machines. Accuracy of fit of removable partial dentures fabricated by conventional techniques and CAD/CAM PEEK dentures have been compared with the latter resulting in comparable, and in some instances, a more superior fit to conventional techniques.<sup>21,22</sup> Moreover, two-body wear test of PEEK was more favorable compared to the other CAD/CAM composite resin and PMMA material.<sup>23</sup> In vitro testing of PEEK molar crowns fabricated on zirconia and titanium abutments in a chewing simulator resulted in acceptable fracture strength property, recommending them for clinical application.<sup>24</sup>

## 2.5 | Metals

Chrome-cobalt, titanium, and noble/high noble gold millable metals have been an appealing addition to the CAD/CAM arsenal of materials due to elimination of miscasting possibilities of the final restoration. Chrome-cobalt is an inexpensive corrosion resistant metal that has been used as a framework for crowns and fixed partial dentures followed by layering of porcelain. Solid-state chrome-cobalt pucks can be milled in robust milling machines, or a "softer" chrome-cobalt material can be milled like wax and further sintered in an argon gas environment to produce a solid-state chrome-cobalt metal. Titanium blocks can be milled to produce custom-made abutments which can further be anodized to desirable colors for more challenging esthetic cases. Noble and high noble alloys can be milled eliminating issues related to spruing, burnout, and casting; providing faster results with less effort than conventional methods.

## 2.6 | Ceramics

Many different types of millable ceramics for CAD/CAM technologies are available. Selection process can be overwhelming and may lead to the

improper selection of a ceramic when lacking proper information and scientific documentation of the properties of these ceramics. Classifying the different CAD/CAM ceramic materials can be according to the following:

1. Infiltrated ceramics/resins (commonly known as hybrid ceramics)
2. Silicate ceramics:
  - Feldspathic ceramics
  - Leucite-reinforced ceramics
  - Lithium disilicate ceramics
3. Oxide or polycrystalline ceramics
  - Aluminum oxide ceramics
  - Zirconium oxide ceramics

- 3 mol% yttria-tetragonal zirconia polycrystals (3Y-TZP)
- 4 mol% yttria-partially stabilized zirconia (4Y-PSZ)
- 5 mol% yttria-partially stabilized zirconia (5Y-PSZ)

## 2.7 | Infiltrated ceramics/resins

This category of CAD/CAM ceramic blocks consist of two types: blocks that contain a polymer matrix infiltrated with ceramic filler particles (eg, Lava Ultimate, 3M ESPE and Katana Avencia Block, Kuraray Noritake, Tokyo, Japan, and Cerasmart, GC International AG, Luzern, Switzerland), and blocks that have a ceramic network infiltrated with a polymer (eg, VITA Enamic). The highlighted properties of these blocks are: high load capacity, fatigue resistance, superior modulus of elasticity, favorable milling characteristics with smoother margins, no crystallization or sintering, and hand polishing required after milling.<sup>25,26</sup> The bonding strategy is different between the different types of these ceramic blocks. The ceramic structure of the polymer-infiltrated ceramics requires acid-etching with 5% hydrofluoric acid for 60 seconds followed by application of a silane coupler. However, the

**TABLE 2** CAD/CAM composite resins composition, properties, and preparation requirement

Properties	Brilliant	Paradigm MZ100	Tetric CAD
Composition	70% glass and silica	85% zirconia-silica	Barium glass (64%), silica (7.1%), and dimethacrylates (28.4%)
Fracture toughness (MPa m <sup>1/2</sup> )	1.41 ± 0.41 <sup>16</sup>	0.78 ± 0.21 <sup>17</sup>	NP
Flexural strength (MPa)	198 ± 14 <sup>18</sup>	157 <sup>19</sup>	NP
Modulus of elasticity (GPa)	10.30 <sup>18</sup>	12.60 <sup>19</sup>	10.20 <sup>a</sup>
Biaxial strength (MPa)	284.22 <sup>a</sup>	NP	273.80 <sup>a</sup>
Water sorption (µg/mm <sup>3</sup> )	23 <sup>a</sup>	NP	22.5 <sup>a</sup>
Fracture load (Newton)	1580 ± 521 <sup>19</sup>	1826 ± 564 <sup>20</sup>	~2600 <sup>a</sup>
Vickers hardness (VH)	82.61 <sup>11</sup>	NP	NP
Minimum wall thickness occlusal	NP	1.50-2.00 mm	NP
Minimum wall thickness circumferential	NP	1.50 mm	NP

Abbreviation: NP, not provided.

<sup>a</sup>Data from the manufacturer.

highly polymerized resin matrix of the ceramic-infiltrated polymer blocks such as Lava Ultimate, requires these ceramics to be pretreated with ≤50 µm aluminum-oxide particle abrasion followed by application of silane.<sup>27</sup> Wear resistance of polymer-infiltrated ceramics are superior to ceramic-infiltrated polymers, however, both are less wear resistant than ceramic restorations.<sup>28</sup> Ceramic-infiltrated blocks are recommended for veneers, inlays/onlays, while polymer-infiltrated ceramic blocks can also be used for single crowns. Clinical trials are still lacking for these ceramics to consider as a viable option for indirect restorations. Various properties, preparation requirements, and compositions of resin-based ceramics can be found in Table 3.<sup>11,13,18,19,21,28-32</sup>

## 2.8 | Silicate ceramics

Silica-based ceramics contain a glassy matrix and are therefore translucent and able to mimic the optical properties of enamel and dentin, making them ideal for restoration of teeth in the esthetic zone. This also makes them brittle and have low fracture resistance which can be mostly compensated by adhesively bonding the restoration. Traditional feldspathic porcelain has the most optimum optical

characteristics and is also considered the weakest among the glass-based ceramics. This type of porcelain requires etching with 9.6% hydrofluoric acid for 1 minute followed by ultrasonic bathing of the restoration to remove any salt residues and then the application of the silane coupler. Efforts to enhance the strength of feldspathic ceramics were attempted through reinforcing the matrix with leucite. Leucite-reinforced ceramics (IPS Empress CAD, Ivoclar Vivadent) have great optical characteristics making them ideal for restorations in the esthetic zone. However, their strength was only enhanced minimally compared to traditional feldspathic porcelain making them a poor selection for load-bearing areas as better options are available. Leucite-reinforced ceramics are adhesively bonded to the tooth by applying 4.9% hydrofluoric acid for 1 minute followed by ultrasonic cleaning and application of the silane. Lithium disilicate ceramics were then introduced containing 72% lithium and silicate oxides, enhancing the strength of glass-based ceramics significantly and still maintaining great optical characteristics. Lithium disilicate ceramics are adhesively bonded to the tooth structure using 4.9% hydrofluoric acid for 20 seconds followed by ultrasonic cleaning and silane application.

### 2.8.1 | Feldspathic porcelain

Millable feldspathic porcelain is considered one of the oldest blocks used in CAD/CAM dentistry. Popular brands include CEREC Blocs (Dentsply Sirona, York, Pennsylvania) and VITABLOC (Mark II, Real-Life, TriLux, VITA Zahnfabrik) that come in color and translucency gradations to better match the natural teeth. The indications for millable feldspathic ceramic materials include veneers, inlays, onlays, and anterior crowns. Clinical trials indicate acceptable success rates for feldspathic CAD/CAM blocks ranging from 84%-95% over a period of 9-18 years.<sup>33-36</sup> Major cause of failure was fracture of the restoration. Favorable prognosis for these ceramics occurs when taking restoration size and location into consideration when planning.

### 2.8.2 | Leucite-reinforced ceramics

First introduced by Ivoclar as IPS Empress CAD and a slight improvement in mechanical properties compared to traditional feldspathic ceramic blocks, these ceramics possess high translucency making them a popular choice for esthetic demanding cases. These ceramic blocks showed good clinical success when used in non-load-bearing areas.

### 2.8.3 | Lithium disilicate ceramics

Lithium disilicate ceramic blocks (eg, IPS E.max CAD, Ivoclar Vivadent) have a crystalline phase consisting of lithium disilicate and lithium orthophosphate, making them successful, at a specified thickness, in load-bearing areas while maintaining enhanced optical properties, making them the ceramic of choice for veneers, inlays/onlays, single crowns. They are milled wet in a precrystallized phase (purple block),

**TABLE 3** CAD/CAM infiltrated ceramics/resins composition, material properties, and preparation requirement

Properties	Cerasmart	Lava Ultimate	Grandio blocs	HC block CAD/CAM	Katana Avencia	VITA Enamic
Composition	71% silica and barium glass	80% silica and zirconia	86% nanohybrid filler	Silica powder, microfumed silica, and zirconium silicate	Silica, alumina, dimethacrylates	Silica (63%), alumina (23%), and sodium oxide (11%)
Fracture toughness (MPa m <sup>1/2</sup> )	1.22 ± 0.20 <sup>19</sup>	1.60 <sup>19</sup>	NP	NP	1.47 ± 0.28 <sup>19</sup>	1.23 ± 0.02 <sup>29</sup>
Flexural strength (MPa)	219 <sup>18</sup>	191 ± 2.70 <sup>25</sup>	208 <sup>26</sup>	191 <sup>26</sup>	230 <sup>a</sup>	152 ± 2.90 <sup>29</sup>
Modulus of elasticity (GPa)	7.90 <sup>18</sup>	10.80 <sup>18</sup>	11.10 <sup>10</sup>	9.50 <sup>10</sup>	NP	22.10 <sup>18</sup>
Biaxial strength (MPa)	238 <sup>a</sup>	193 <sup>a</sup>	333 <sup>a</sup>	NP	NP	130 <sup>28</sup>
Water sorption (µg/mm <sup>3</sup> )	22.0 ± 0.7 <sup>a</sup>	30.70 ± 0.30 <sup>11</sup>	16.90 ± 1.30 <sup>11</sup>	39.70 ± 1.30 <sup>11</sup>	NP	7.00 ± 0.70 <sup>12</sup>
Water solubility (µg/mm <sup>3</sup> )	−0.20 ± 0.20 <sup>11</sup>	−0.40 ± 0.30 <sup>11</sup>	−2.70 ± 0.50 <sup>11</sup>	0.60 ± 0.50 <sup>11</sup>	NP	−2.80 ± 0.00 <sup>12</sup>
Fracture load (Newton)	1522 ± 352 <sup>27</sup>	2111 ± 500 <sup>28</sup>	~2000 <sup>a</sup>	~1200 <sup>a</sup>	3750 <sup>21</sup>	2766 ± 98 <sup>a</sup>
Vickers hardness (VH)	80.06 <sup>11</sup>	1.10 ± 0.10 <sup>11</sup>	121.80 <sup>25</sup>	65.30 ± 2.40 <sup>26</sup>	NP	2.30 ± 0.10 <sup>12</sup>
Wear (two-body) (mm <sup>3</sup> )	~105 <sup>a</sup>	~50 <sup>13</sup>	59.90 <sup>a</sup>	NP	NP	~50 <sup>13</sup>
Minimum wall thickness occlusal	1.50 mm	1.50 mm	1.50 mm	NP	1.50 mm	NP
Minimum wall thickness circumferential	1.50 mm	1.50 mm	1.50 mm	NP	1.00 mm	NP

Abbreviation: NP, not provided.

<sup>a</sup>Data from the manufacturer.

then crystallized in a sintering furnace, followed by polishing, stain, and glaze application. Multiple clinical trials and laboratory surveys report favorable clinical outcomes for lithium disilicate single crown restorations.<sup>37,38</sup> However, unfavorable results have been reported for lithium disilicate ceramics as fixed dental prosthesis, mostly fracturing at the connector site.<sup>37</sup>

Recently, modified versions of this category of silicate ceramics have been introduced that are fully crystallized with no need of further crystallization. VITA Suprinity PC (VITA Zahnfabrik), Celtra Duo (Dentsply Sirona), and Obsidian (Glidewell Laboratories, Newport Beach, California) are examples of ceramic blocks that have been recently introduced, claiming mechanical and optical properties similar to IPS E.max CAD. However, clinical trials are lacking for these ceramic blocks. In vitro studies have shown properties either similar, or slightly inferior, to IPS E.max. However, most studies deemed these ceramics to be within clinically acceptable qualities given sufficient thickness.<sup>39,40</sup>

Marginal misfits of lithium disilicate ceramics have been reported to be minimal and within clinically acceptable limits.<sup>41</sup> However, most studies have confirmed that heat-pressed lithium disilicate restorations have better marginal fit the CAD/CAM restorations.<sup>42</sup>

Composition of CAD/CAM silicate ceramics, properties, and preparation requirement can be found in Table 4.<sup>11,12,14,16,29,32</sup>

## 2.9 | Oxide ceramics

Zirconium dioxide (zirconia) are highly dense polycrystalline metal oxide ceramic blocks that have excellent mechanical properties in

their conventional 3 mol% yttria-stabilized zirconia polycrystals (3Y-PSZ) composition with flexural strengths around 1200 MPa (eg, Katana HT, Kuraray Noritake, Japan and Lava Plus, 3M, St. Paul, Minnesota and IPS E.max ZirCAD, Ivoclar Vivadent). The tetragonal particles (85%) undergo phase transformation when a crack starts to propagate, transforming the tetragonal particles to the larger monoclinic particles, forming compressive stresses around the crack tip preventing it from propagating. This phenomenon is referred to as transformation toughening.<sup>43</sup> The first generation lacked translucency, and were required to be veneered with feldspathic porcelain to make them esthetically acceptable. Chipping of the veneering porcelain was a major problem until proper core designs supporting the overlaying porcelain and in addition to gradual cooling of the restoration after sintering was recognized. This reduced the incidence of chipping significantly.<sup>44</sup> The zirconia core rarely fractured and hence the conception of full-contour monolithic zirconia restorations. 3Y-PSZ is a strong ceramic that can be used in heavy load-bearing areas as single crowns and fixed dental prosthesis that can be conventionally cemented to the tooth structure with resin-modified glass ionomer cements, provided proper resistance and retention form. However, the lack of translucency limited their application in esthetic sensitive cases, which encouraged the development of a more translucent monolithic zirconia restoration. By increasing the amount of yttria to 5 mol% and reducing the alumina content, more cubic-phase crystals (55%) are present within the zirconia structure allowing more light to transmit through (eg, Katana UTML and Bruxzir Anterior, Glidewell Laboratories). As the translucency was

**TABLE 4** CAD/CAM silicate ceramics composition, properties, and preparation requirement

Properties	VITA blocs Mark II	Cerec blocs	IPS Empress CAD	IPS E.max CAD	VITA Suprinity PC	Celtra Duo
Composition	Silica (64%) and aluminum oxide (23%)	Silica (64%) and aluminum oxide (23%)	Silica (65%), alumina (20%), and potassium oxide (14%)	Silica (80%), lithium oxide (19%), and potassium oxide (13%)	Silica (64%), lithium oxide (21%), and zirconia (12%)	Silica, lithium dioxide, and zirconium dioxide
Fracture toughness (MPa m <sup>1/2</sup> )	2.34 ± 0.04 <sup>29</sup>	1.70 ± 0.10 <sup>a</sup>	1.90 ± 0.30 <sup>29</sup>	1.80 <sup>19</sup>	2.00 <sup>a</sup>	NP
Flexural strength (MPa)	112.4 ± 3.20 <sup>29</sup>	154 ± 15 <sup>a</sup>	134.5 ± 3.30 <sup>29</sup>	360 ± 60 <sup>32</sup>	420 <sup>32</sup>	210 <sup>32</sup>
Modulus of elasticity (GPa)	48 <sup>11</sup>	45 ± 0.50 <sup>a</sup>	62 <sup>a</sup>	95 ± 5.00 <sup>32</sup>	70 <sup>32</sup>	70 <sup>32</sup>
Biaxial strength (MPa)	77 <sup>17</sup>	NP	160 <sup>a</sup>	295 <sup>39</sup>	240 <sup>39</sup>	≥600 <sup>a</sup>
Fracture load (Newton)	NP	2281 ± 75 <sup>14</sup>	~1200 <sup>a</sup>	2494 ± 116 <sup>14</sup>	NP	NP
Vickers hardness (HV)	6.40 ± 0.10 <sup>29</sup>	6.40 ± 0.20 <sup>a</sup>	6.10 ± 0.10 <sup>29</sup>	5.80 ± 0.10 <sup>29</sup>	7.00 <sup>a</sup>	NP
Wear (two-body) (mm <sup>3</sup> )	~25 <sup>16</sup>	NP	~40 <sup>32</sup>	~35 <sup>32</sup>	155 <sup>a</sup>	NP
Minimum wall thickness occlusal	1.50 mm	2.00 mm	2.00 mm	1.50 mm	1.50 mm	1.50 mm
Minimum wall thickness circumferential	1.00 mm	1.00-1.50 mm	1.50 mm	1.50 mm	1.50 mm	1.50 mm

Abbreviation: NP, not provided.

<sup>a</sup>Data from the manufacturer.

enhanced, the strength of the zirconia was significantly reduced. The transformation toughening phenomenon occurs in the presence of tetragonal particles transforming to monoclinic. In the new generation of zirconia, increased cubic content and reduced tetragonal particles in the zirconia structure minimizes the transformation toughening phenomenon, and therefore allowing more crack propagation to occur, reducing zirconias' strength significantly. The reduced strength mandates this type of zirconia to be adhesively bonded to the tooth structure. Air-particle abrasion with ≤50 µm particles and 2 bar pressure is recommended as a pre-treatment, followed by using a ceramic primer containing the 10-methacryloyloxydecyl dihydrogen phosphate monomer that can bond to metal-oxides. The use of dual-polymerizing cement is required as light energy can be attenuated through zirconia restorations.<sup>45</sup> The use of Ivoclean (Ivoclar Vivadent), a cleaning paste that effectively cleans the zirconia surface after try in, is highly recommended to enhance bond strengths.

Due to increased concerns with the low fracture resistance of 5 mol% yttria-stabilized zirconia, reducing the yttria content to 4 mol%, decreases the cubic content to 25%, enhancing transformation toughening and ultimately the fracture resistance compared to 5 mol% zirconia. Translucency is maintained at an enhanced level compared to conventional 3 mol% yttria zirconia.<sup>46</sup> Examples of this type of zirconia

include (Katana STML, Kuraray Noritake, Japan and Bruxzir Esthetic, Glidewell Laboratories).

Chairside "fast-sintering" CAD/CAM zirconia blocks (eg, 3M Chairside zirconia, 3M and Katana STML) have been introduced to minimize the sintering time from traditional 8 h to 20 min by using special speed-sintering furnaces (eg, CEREC Speedfire, Dentsply Sirona).

Considering the different types of zirconias available, conventional 3 mol% yttria zirconia can be recommended in heavy load-bearing areas where esthetics is not a concern. Yttria zirconias of 5 mol% have been recommended to be used in the esthetic zone. However, with increased concerns over their fracture resistance and the superior esthetic qualities of lithium disilicate ceramics, reservations are warranted using this type of zirconia. Concerning the recently introduced 4 mol% yttria zirconias, they may serve as an alternative to 5 mol% zirconias in the esthetic zone. It is recommended to cut back the zirconia facially and layer with feldspathic porcelain to achieve optimum esthetics. Long-term clinical trials are required for all types of monolithic zirconia restorations, passing the test of time, in order to recommend these ceramic restorations as a definite alternative to traditional gold and porcelain fused to metal restorations. Composition of CAD/CAM oxide ceramics, properties and preparation requirement can be found in Table 5.<sup>46-48</sup>

**TABLE 5** CAD/CAM oxide ceramics properties, preparation requirement, and composition

	Cerrec zirconia	Katana HT	Katana STML	Katana UTML	VITA YZ HT	Lava esthetic zirconia	IPS E.max ZirCAD (3Y)	IPS E.max ZirCAD (4Y)	IPS E.max ZirCAD (5Y)
Composition	Zirconia (99%) and yttria (4.5%-6.0%)	Zirconia and yttria	Zirconia and yttria	Zirconia and yttria	Zirconia (95%), yttria (6%), and hafnia (3%)	Zirconia (95%) and yttria (5%)	Zirconia (95.5%), yttria (6%), and hafnia (5%)	Zirconia (93.5%), yttria (8%), and hafnia (5%)	Zirconia (93.5%), yttria (8%), and hafnia (5%)
Fracture toughness (MPa m <sup>1/2</sup> )	7.10 <sup>a</sup>	3.50-4.50 <sup>46</sup>	2.50-3.50 <sup>46</sup>	2.20-2.70 <sup>46</sup>	4.50 <sup>a</sup>	3.00-5.00 <sup>a</sup>	5.00 ± 0.25 <sup>a</sup>	3.75 ± 0.25 <sup>a</sup>	2.40 ± 0.25 <sup>a</sup>
Flexural strength (MPa)	NP	1194 ± 111 <sup>47</sup>	748 <sup>a</sup>	557 <sup>a</sup>	1106 ± 97 <sup>48</sup>	800 <sup>a</sup>	1157 ± 100 <sup>48</sup>	850 <sup>a</sup>	850 <sup>a</sup>
Modulus of elasticity (GPa)	NP	205 <sup>46</sup>	NP	NP	210 <sup>a</sup>	NP	NP	NP	NP
Biaxial strength (MPa)	NP	889.9 <sup>46</sup>	507.6 <sup>46</sup>	470.2 <sup>46</sup>	635 <sup>47</sup>	NP	1200 <sup>a</sup>	NP	850 <sup>a</sup>
Minimum wall thickness occlusal	1.00 mm	0.50 mm	1.00 mm	1.00 mm	0.50 mm	0.80 mm	0.60 mm	1.00 mm	1.00 mm
Minimum wall thickness circumferential	0.80-1.00 mm	0.50 mm	1.00 mm	1.00 mm	0.40 mm	0.80 mm	0.60 mm	1.00 mm	1.00 mm

Abbreviation: NP, not provided.  
<sup>a</sup>Data from the manufacturer.



### 3 | ADDITIVE MANUFACTURING

Also referred to as 3D printing, this recent and emerging technology has gained a lot of interest in the dental field due to its wide-range capabilities for providing surgical guides, temporary restorations, occlusal splints, bite-guards, scaffolds, and orthodontic appliances. AM allows building up pieces by adding materials (composites, metals, and ceramics) layer-by-layer, based on a computerized 3D model.<sup>49</sup> This process seems to be promising and may be the future of how most dental restoration/appliances are delivered. However, it is important to investigate the current materials available for AM, their properties, durability, and surface characteristics to evaluate if they are a viable replacement to conventional materials or materials processed through SM.

AM provides the following benefits:

- Reduces material waste and consumes less energy.
- Minimizes the number of steps to reach the final product, and therefore requires less human intervention and possibility for error.
- Produce intricate details at a predictable cost.

There are seven categories of AM technologies: stereolithography (SLA), material jetting (MJ), material extrusion or fused deposition modeling, binder jetting, powder bed fusion, sheet lamination, and direct energy deposition.<sup>50</sup> The SLA and MJ technologies are the most used in dentistry. The quality of the printed object depends on the capabilities of the 3D printer. Certain factors such as resolution or accuracy, precision, and trueness define the capability of a 3D printer.

#### 3.1 | AM of polymers

Conventional provisional materials are classified into monomethacrylates or acrylic resins and dimethacrylates or bis-acryl/composite resins such as bisphenol A-glycidyl dimethacrylate and light-polymerizable urethane dimethacrylate.<sup>51</sup> It is unclear and lacking in the literature whether printable polymers are identical to conventional, due to the difference in processing method. It is encouraged for further studies to chemically analyze 3D printable polymers.

Provisional restorations are required to support function and esthetics until a definite restoration is fabricated. It is important for these materials to have adequate mechanical properties, accuracy of fit, color stability, and hardness in order to fulfill its role. Many properties of conventional provisional materials have been reported.<sup>52-54</sup> The flexural strength and microhardness of a printable hybrid composite resin was compared to a milled and a conventional PMMA material. The flexural strength of the printable composite resin (79.5 MPa) was significantly lower than the conventional (95.6 MPa) and milled (104.2 MPa) PMMA. The microhardness of the printable composite resin (32.8) was higher than the conventional and milled PMMA (27.4 and 25.3, respectively).<sup>55</sup> Vertically printed specimens with layers oriented perpendicular to the load direction presented significantly

higher compressive strength than horizontally printed specimens with layers parallel to load direction.<sup>56</sup> Properties of printable polymers are scarce, and therefore it is difficult to make recommendations concerning the minimal dimensions required for connector areas of provisional fixed dental prosthesis, or number of pontics possible. The durability and longevity of these materials in clinical scenarios are also missing. Can these materials be repaired or relined with conventional polymers? Many questions remain to be answered before making clinical recommendations for printable polymers.

#### 3.2 | AM of ceramics

Due to the high melting point of ceramics, it makes the AM process quite complicated that results in crack formation during the cooling process, also increasing the porosity within the ceramic. Crack propagation and porosities weaken the ceramic reducing the mechanical properties. Attempts to print a zirconia crown were achieved by direct inkjet printing using zirconia ceramic suspensions. The outcome was not free from flaws; however, it was possible to produce samples that were comparable to conventionally prepared zirconia material.<sup>57</sup> SLA processing methods have been used to make zirconia crowns with outcomes superior to inkjet printing methods, and mechanical and surface properties similar to milled zirconia.<sup>58</sup> SLA printing methods have also been utilized to print zirconia implants. The dimensional accuracy of the printed implant was high, and the achieved mechanical properties showed flexural strength (943 MPa) close to those of conventionally produced ceramics (milled zirconia 800-1000 MPa).<sup>59</sup> AM has been explored with other ceramics and calcium phosphate compositions as scaffolds mainly used for bone regeneration with promising outcomes. However, the inherent challenges of 3D printing should not be overlooked. Aspects such as surface quality, dimensional accuracy, and the mechanical properties need improvement to allow producing effective high-quality products. Further developments of AM technology are expected to give a significant contribution to bring production costs down, improve manufactured materials properties, and render the production processes more efficient and competitive.<sup>60</sup>

#### 3.3 | AM of metals

Selective laser sintering is the technology used for the production of metal-based appliances mainly out of titanium, chrome-cobalt, and other alloys. Early trials of this technology resulted in products that were porous, with poor surface finishing, and inefficient for load-bearing areas. Development in this technology has focused to overcome these deficiencies resulting in metallic structures with optimal mechanical properties and minimized surface irregularities that enhance osseointegration in implant cases.<sup>61,62</sup> Direct metal laser sintering has been successfully used to overcome difficulties with chrome-cobalt appliances such as shrinkage during casting and high hardness of CoCr during milling as there is no active force application

TABLE 6 Additive manufacturing materials composition, properties, and preparation requirement

Properties	Freeprint Temp	Temporis	VarseoSmile Temp	VarseoWax surgical guide	E-Dent 400	Denture 3D+	C&B MFH	Whip mix surgical guide	Dentca Denture Base II	Dentca denture teeth	Dreve FotoDent denture	Keysplint Soft Clear
Composition	NP	Multifunctional acrylic monomers and esters of acrylic acid	NP	NP	NP	Monomer based on acrylic esters	NP	Bisphenol A ethoxylate dimethacrylate 4, phenyl-bis(2,4,6-trimethylbenzoyl) phosphine oxide	Composition	NP	Multifunctional acrylic monomers and esters of acrylic acid	NP
Fracture toughness (MPa m <sup>1/2</sup> )	NP	NP	NP	NP	NP	NP	1.42 + 0.09	NP	NP	NP	NP	NP
Flexural strength (Mpa)	NP	85-135 <sup>a</sup>	≥80 <sup>a</sup>	≥50 <sup>a</sup>	85 <sup>a</sup>	84 <sup>a</sup>	91.8 + 6.3	90 <sup>a</sup>	<65 <sup>a</sup>	<50 <sup>a</sup>	<95	47 <sup>a</sup>
Flexural modulus (GPa)	NP	2900-4200 <sup>a</sup>	≥2000 <sup>a</sup>	≥1500 <sup>a</sup>	2100 <sup>a</sup>	2382 <sup>a</sup>	2374 + 118	NP	<2000 <sup>a</sup>	NP	<2200	1356 <sup>a</sup>
Biaxial strength (MPa)	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Water sorption (µg/mm <sup>3</sup> )	NP	<40 <sup>a</sup>	NP	NP	30 <sup>a</sup>	0.1	54 <sup>a</sup>	NP	NP	NP	NP	<84.8 <sup>a</sup>
Water solubility (µg/mm <sup>3</sup> )	NP	<1.4 <sup>a</sup>	NP	NP	5 <sup>a</sup>	<0.1	5.9 <sup>a</sup>	NP	NP	NP	NP	NP
Vickers hardness (VH)	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Wear (two-body) mm <sup>3</sup>	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Minimum wall thickness occlusal	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
Minimum wall thickness circumferential	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP

Abbreviation: NP, not provided.  
<sup>a</sup>Data from the manufacturer.

during the fabrication of structures. In addition, low amount of material wastage has made this technology popular particularly with precious alloys. Composition of AM materials, properties and preparation requirement can be found in Table 6.<sup>63-65</sup> Various properties have not been reported and highlighted in Table 6 to point out the properties missing and encourage further research to fill this empty gap.

## 4 | CONCLUSIONS

CAD/CAM technology has changed the way dentistry is practiced, and care is delivered. Deficient areas that require finesse will inevitably be addressed as constant development in technology and quality of materials transpire. Laboratory and chairside milling units are more versatile and capable of milling multiple materials with properties that may ensure a long-term clinical success. AM is an alternative and promising manufacturing method of dental restorations and appliances. The technology of additive techniques allows for fabrication of more sophisticated build structures without excessive force and much less non-recyclable waste when compared to SM techniques. Materials produced from SM have a longer track record of clinical evidence compared to AM material, although recently introduced material are still lacking sufficient clinical evidence. *in vitro* testing of the basic mechanical, physical, and optical properties is useful; however, they need to be interpreted with caution before claiming clinical outcomes. As more clinical trials evaluating materials from both SM and AM are required, utilization of these materials should be done with caution.

## CONFLICT OF INTEREST

The author has no financial interest in any of the companies whose products are mentioned in this review.

## ORCID

Taiseer A. Sulaiman  <https://orcid.org/0000-0002-3826-316X>

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