

2016

# The effects of machining on the flexural strength of CAD-CAM materials

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BOSTON UNIVERSITY  
HENRY M. GOLDMAN SCHOOL OF DENTAL MEDICINE

THESIS

**THE EFFECTS OF MACHINING ON THE FLEXURAL STRENGTH  
OF CAD-CAM MATERIALS**

by

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Submitted in partial fulfillment of the requirements for the degree of

Master of Science in Dentistry

In the Department of Restorative Sciences and Biomaterials

2016

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## **Acknowledgments**

I would like to thank Allah for his benevolence, mercy and guidance.

To my parents and my wife, their constant encouragements and support during my studies was the source of my drive.

I would like to thank Dr. Giordano, my major advisor, for his mentorship, help and insight during my research time. I would also like to thank Dr. Fan for tirelessly helping me refine and improve my work and showing me how to conduct scientific research.

I would like to thank Dr. Nathanson for accepting me into the program and for sharing his experience in dentistry and in life.

I would like to thank Dr. Yamamoto for his time and effort in teaching me. His high standards and expectations exemplify the ideal that I want to reach.

I would like to thank Dr. Al-Haddad, his friendship, especially in my last year, made my experience more enjoyable

# **THE EFFECTS OF MACHINING ON THE FLEXURAL STRENGTH OF CAD-CAM MATERIALS**

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## **ABSTRACT**

### Objectives

To evaluate the effects of different machining modes on the flexural strength CAD-CAM restorative materials.

### Materials and Methods

Four different CAD-CAM materials were used: VITA MARKII, VITA Enamic (VITA Zahnfabrik), Empress CAD, and e.max CAD (Ivoclar Vivadent). Rectangular bars for each material (except e.max CAD) were made by three procedures: saw cut, normal mill and fast mill. Each subgroup had a sample size of 5. Saw cut bars were cut by a BUHLER diamond blade saw. Milled bars were made using SIRONA CEREC MCXL milling unit. The 3-point flexural strength test was performed using a universal testing machine. Surface roughness was measured using a profilometer. Student t-test and Tukey-Kramer statistical analysis were performed to check significant differences.

## Results

e.max CAD saw cut group was significantly stronger than the milled group. There was no difference in the strength of the Empress CAD groups. Enamic saw cut group was significantly stronger than the normal milled but not the fast milled one. There was no significant difference between the Enamic milled groups. Vita MKII saw cut was significantly stronger than both milled groups. There was no difference in the strength between the milled MKII groups.

The surface roughness of the saw cut groups in all materials were significantly less than their milled counterparts in both longitudinal and transverse measurements.

## Conclusion

Machining had a significant effect on the surface roughness of materials. Damage from machining can cause the material to have lower flexural strength.

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## Chapter 1. Introduction

Digital dentistry has become an integral part of the profession. CAD/CAM dental technology has started around 1971 with Dr. Francois Duret, where he created the first dental milling machine. In 1983, he produced the first dental CAD/CAM restoration. The first CEREC machine was available in 1985, producing a chairside inlay.<sup>1,2</sup> Since then, the technology has become more versatile, offering the dentist a range of choices from single teeth restorations (eg. Inlays, onlays, crowns) to multiple teeth restorations (eg. FPDs, frameworks).<sup>2</sup> Figure 1, shows a photo of a CEREC MC XL milling unit and the scanner.

Typically, CAD/CAM systems consist of:<sup>3</sup>

- An Optical scanner that scans the patient's mouth or a stone cast, then creating a digital model
- A software that enables the user to design the desired restoration
- A milling unit that will fabricate the designed restoration



Figure 1: CEREC MC XL milling unit and scanner

The use of CAD/CAM restorations has introduced many advantages. The ability to use uniform blocks has helped in regulating the quality of restorations produced.<sup>2,4</sup> The prefabricated blocks have less internal defects making for stronger restorations.<sup>1,5</sup> Another advantage of CAD/CAM technology is the ability to reproduce the restorations when needed from a computer file.<sup>1,4</sup> Furthermore, through the use of CAD/CAM technology can lead to fewer dental visits and reduction in production costs.<sup>4,6</sup> However, CAD/CAM restoration systems have some disadvantages. The initial entry cost is high (Scanner and milling unit). Also, there is a learning curve to be become proficient in using this technology.<sup>7</sup>

There are two variables (other than clinical skills) that can influence and determine the quality of the CAD/CAM restorations: The milling machine being used and the type of block material that is incorporated.<sup>8</sup>

## **1.1 Types of Ceramics**

There are many types of ceramics that have been incorporated into the use of CAD/CAM restorations. These ceramics can be categorized based on their composition of glass to crystalline ratio. Glass ceramics are one of the more popular available porcelains. The main composition of these ceramics is silicon dioxide (silica) that also contains some alumina.<sup>9</sup>

One example is feldspathic porcelain, such as VITA MARKII produced by VITA Zahnfabrik.<sup>8</sup> The VITA MKII has been introduced in 1991.<sup>10</sup> The chemical composition of the VITA MKII is  $\text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{Na}_2\text{O} - \text{K}_2\text{O}$ .<sup>11</sup> The MKII blocks are made of fine grain, that have a particle size of  $4\mu$ .<sup>10</sup> The blocks are made of feldspathic ceramic that is produced through an extrusion moulding process. This is followed by drying then sintering of the moulds.<sup>12</sup> This results in the productions of blocks that are almost pore-free with finer crystal content.<sup>8</sup> Study reports have shown that MKII blocks have shown flexural strength of 100 MPa and can increase to 160 MPa after polishing.<sup>8, 10, 13</sup> The esthetic nature of the ceramic and its strength makes it appropriate for the use of veneers and partial coverage restorations such as inlays and onlays.<sup>12, 14</sup>

Another category of glass ceramics is ones that contain filler content. One typical crystalline filler used is leucite. These ceramics are formed through pressing process. A ceramic ingot is placed into a plunger and is heat pressed into an investment mold.<sup>9</sup>

The first leucite reinforced ceramic block developed for the CEREC machine was introduced in 1998, was the ProCAD made by Ivoclar Vivadent.<sup>12, 15</sup> Later in 2006, Ivoclar introduced IPS Empress CAD that improved on the production process using finer crystal size of the leucite which accounts for 45% of the volume.<sup>12</sup> The leucite crystals are spaced  $1-5\mu\text{m}$  within the glass matrix.<sup>10</sup> The glass phase composition of the Empress CAD block is  $\text{SiO}_2 - \text{Al}_2\text{O}_3 - \text{K}_2\text{O}$  and the leucite crystal composition is  $\text{KAlSi}_2\text{O}_6$ .<sup>16</sup> The manufacturing process is done through initially pressing the powder then sintering the blocks.<sup>12</sup> The addition of the leucite contributes to the decrease in the machining damage caused from

the milling process and to reducing crack propagation and improved properties.<sup>12,15</sup> The reported flexural strength of the Empress CAD is 160MPa.<sup>16</sup> Empress CAD blocks are available in a range of shades and translucencies.<sup>12</sup> Based on the manufacturers recommendation, Empress CAD restoration are used for single teeth restorations.<sup>9</sup>

Lithium disilicate reinforced ceramics are another type of ceramic. Ivoclar introduced this material in 1998 as Empress II.<sup>17</sup> The compositional structure of this ceramic is  $\text{SiO}_2\text{-Li}_2\text{O-K}_2\text{O-ZnO-P}_2\text{O}_5\text{-Al}_2\text{O}_3\text{-La}_2\text{O}_3$ , with the lithium disilicate crystals,  $\text{Li}_2\text{Si}_2\text{O}_5$ , accounting for 70% by volume.<sup>18, 19</sup> Similar to leucite reinforced ceramics, Lithium disilicate ingots are heat pressed to form the desired restoration except at a lower temperature.<sup>9, 19</sup> The lithium disilicate crystals are  $5\mu$  after final crystallization and are interlocked. In addition to that, the difference in the coefficient of thermal expansion of the lithium disilicate crystals and the glassy matrix help in improving the strength of the ceramic. The reported strength of the ceramic is 350 MPa.<sup>19</sup> The strength of the material made it popular in the use for single teeth restorations including in posterior teeth, as well as framework for anterior FPDs. However, the opaque nature of the porcelain made it necessary to have it veneered to improved esthetics.<sup>17</sup>

Developed with improved mechanical and esthetic properties, in 2006, Ivoclar introduced e.max press as the successor to Empress II.<sup>12</sup> The composition system for e.max is  $\text{SiO}_2\text{-Li}_2\text{O-K}_2\text{O-ZnO-P}_2\text{O}_5\text{-Al}_2\text{O}_3\text{-ZrO}_2$ . Through modifying the firing process, reported flexural strength of the material is around 450 MPa.<sup>12, 19</sup> Furthermore, e.max ingots are available in multiple translucencies and shades allowing the material to be more versatile.<sup>12</sup>

e.max has been recommended to be used for both anterior and posterior restorations, and due to improved esthetics can be used as core material or as final restoration.<sup>12, 19</sup>

Ivoclar has also produced e.max CAD blocks (Figure 2) to be used for milled chair side restorations. The available blocks come in a partially crystallized state termed “blue state”.<sup>12</sup> At this state the blocks contain meta silicate, that account for 40% volume, and disilicate nuclei and have a flexural strength of around 160MPa, making them easier to mill. Once the restoration is milled, it is fired at around 850°C to achieve final crystallization. At this point the restoration changes its color to the appropriate tooth shade and the meta crystals dissolve leaving the lithium disilicate crystals and achieving the final strength.<sup>12, 19</sup> In the final form, the ceramic has a crystal content of 70% with the crystal size at 1.5 μm.<sup>12</sup>

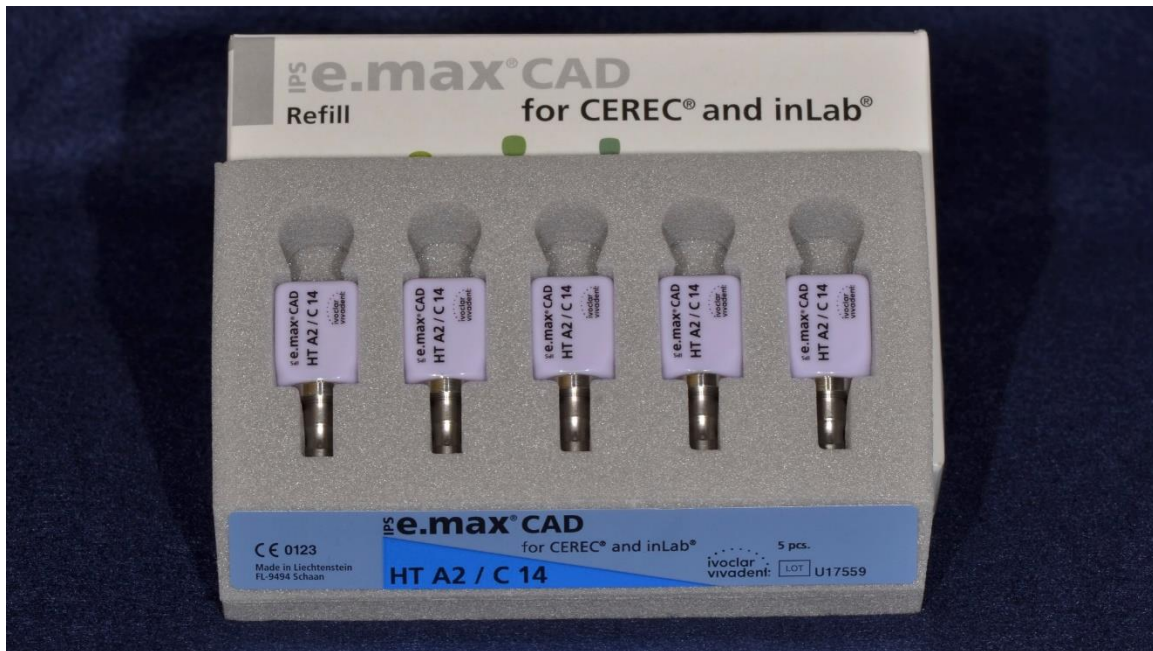


Figure 2: e.max CAD blocks

A new type of polymer infiltrated ceramic network material has been recently introduced by VITA Company.<sup>20</sup> The concept of development is based on infiltrated ceramics, similar to VITA Inceram, where the ceramic is slip casted and has two interpenetrating phases, a porous ceramic phase and a glass phase.<sup>12, 20, 21</sup> The new ceramic, named VITA Enamic, replaces the glass phase with a poly methyl methacrylate polymer.<sup>18</sup>

The reported composition of the ceramic component of Enamic is SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, K<sub>2</sub>O, B<sub>2</sub>O<sub>3</sub> CaO, TiO<sub>2</sub>.<sup>22</sup> This accounts for 86% wt and 75% vol.<sup>23</sup> The composition of the polymer part is UDMA (urethane dimethacrylate) and TEGDMA (triethylene glycol dimethacrylate). By comparison, the polymer component account for 14% wt and 25% vol. The reported flexural strength of Enamic is 160 MPa.<sup>23</sup>

By replacing the glass phase with the polymer the intention is to reduce the brittle nature of the ceramic, and improve the flexibility of the material.<sup>24</sup> This can lead to improved fracture toughness and reduced crack propagation. It is also has been reported that Enamic can be used for restorations where space limitations are a concern.<sup>20, 22</sup>

## **1.2 Machining Process of CAD/CAM**

There are a variety of methods available for fabricating CAD/CAM restorations. This includes: laser assisted machining, electro-discharge machining, abrasive jet machining, chemically assisted machining. However, the most popular technique used in CAD-CAM restorations is form grinding.<sup>25</sup> Form grinding is an abrasive procedure where a grinding

tool (bur) is used to cut and remove the ceramic surface. This type of manufacturing is known to cause surface and sub-surface damage to the fabricated restorations, which can lead to the formation of cracks that can cause failure of the restorations.<sup>26</sup> This manufacturing method also results in residual stress within the final restoration that may affect its strength.<sup>27</sup> Furthermore, due to potential machining damage, the strength of the ceramics used in CAD/CAM restorations may differ from what is reported by the manufacturer.<sup>11</sup> It is noteworthy that the CEREC MC XL unit offers different milling options for the restorations. This includes a fast mill options that reduces the milling time by %40. This however creates a rougher surface resulting in higher chance of chipping at the margin.<sup>28</sup>

### **1.3 Flexural Strength and Surface Roughness**

One of the important parameters considered in material selection is the strength of the ceramic. Dental restorations in the mouth undergo both compression and tension, which can cause bending of the ceramic. In this sense, the use of flexural strength as a parameter can be considered a good estimate of the performance of the material.<sup>18</sup> The three point bending test and the four point bending (bi-axial) test have been commonly used as a test for measuring flexural strength of ceramics.<sup>29</sup> Static load is applied on specimen until it fractures. It is worth noting that ceramics are prone to edge failure and this can be observed more during the three point test.<sup>30</sup>

Another parameter that can affect the quality of dental restorations is their surface roughness.<sup>14</sup> Surface roughness can be defined as the irregularities in the material (in this case the ceramic) resulting from the machining process. There are several methods in which the surface roughness can be measured, but most commonly the average surface roughness is used as to quantify the parameter. A profilometer is used to measure the average peaks and valleys of the specimen in a given span. The arithmetic average measured from the movement of the profilometer across the sample length is designated the symbol  $R_a$  is used to represent the surface roughness.<sup>31</sup>

When considering the effects of surface roughness on the quality of ceramic restoration it has been observed that plaque will accumulate more on restorations with higher surface roughness potentially causing higher risk of dental caries and periodontal disease.<sup>14</sup> Additionally, studies have shown a link between surface roughness and the flexural strength of ceramics.

Numerous studies have been conducted examining the link between surface roughness and flexural strength. In a study that tested the correlation between surface roughness and the flexural strength of ceramic veneers found that flexural strength increased with reduced surface roughness.<sup>32</sup> Another study by Flury *et. al.*<sup>33</sup>, tested Vita MKII blocks and Empress CAD blocks, found an increase in flexural strength of the specimen blocks improved with decreasing surface roughness. de Jager *et. al.*<sup>34</sup> also examined the relationship between surface roughness and the strength of ceramics and demonstrated that there is an inverse relationship between surface roughness and strength.

Different methods have been proposed to reduce surface roughness. Both polishing and glazing of the ceramics are popular methods that are used. When examining IPS Empress and Empress 2, Albakry *et. al.*<sup>35</sup> found that when polished, the flexural strength improved significantly compared to sandblasted and ground groups. Chen *et. al.*<sup>36</sup> studied the effects of glazing and polishing on CAD/CAM and pressed crowns. They concluded that glazing improved the ProCAD crowns strength significantly. Another study by Giordano *et. al.*<sup>37</sup> revealed techniques such as ion exchange, over glazing and polishing ceramics improved their flexural strength.

However, a study by Ahmad *et. al.*<sup>38</sup> showed that polishing ceramics at 20000 rpm reduced the flexural strength. Furthermore, they observed that over glazing did not improve the flexural strength. Another study by Addison *et. al.*<sup>26</sup> examined the effects of annealing on machined Vita Mark II disks; found that annealing did not improve the surface roughness or flexural strength.

Although extensive research had been conducted on the currently available CAD/CAM ceramics, very few have been conducted with machined specimens made by the milling machine. It is important to study the materials under the same conditions they will be fabricated for intra oral use.

## **Study Objectives**

- Examine the effects of different machining modes on the surface roughness of different CAD/CAM ceramics
- Compare the flexural strength of the machined and saw cut materials.

## Hypothesis

- The null hypothesis is:
  - There is no significant difference in the surface roughness of the ceramics in the different groups
  - The flexural strength of the ceramics is not effected by the different machining modes

## Chapter 2. Materials and Methods

### 2.1 Materials

The materials included in this study are:

Table 1:List of CAD/CAM ceramics used in the study

<b>Material</b>	<b>Manufacturer</b>	<b>Composition</b>
e.max CAD	Ivoclar vivadent	Lithium disilicate
Empress CAD	Ivoclar Vivadent	Leucite glass-ceramic

Vita MKII	Vita Zahnfabrik	Feldspar
Enamic	Vita Zahnfabrik	Feldspar ceramic with added polymer

## 2.2 Methods

CAD/CAM blocks of the mentioned ceramics (Table 1) were used for this study. Bars have been fabricated from each material and were divided into three groups for testing. The specimen size for each group was 5. Figure 3 outlines the tested groups and parameters of the study.

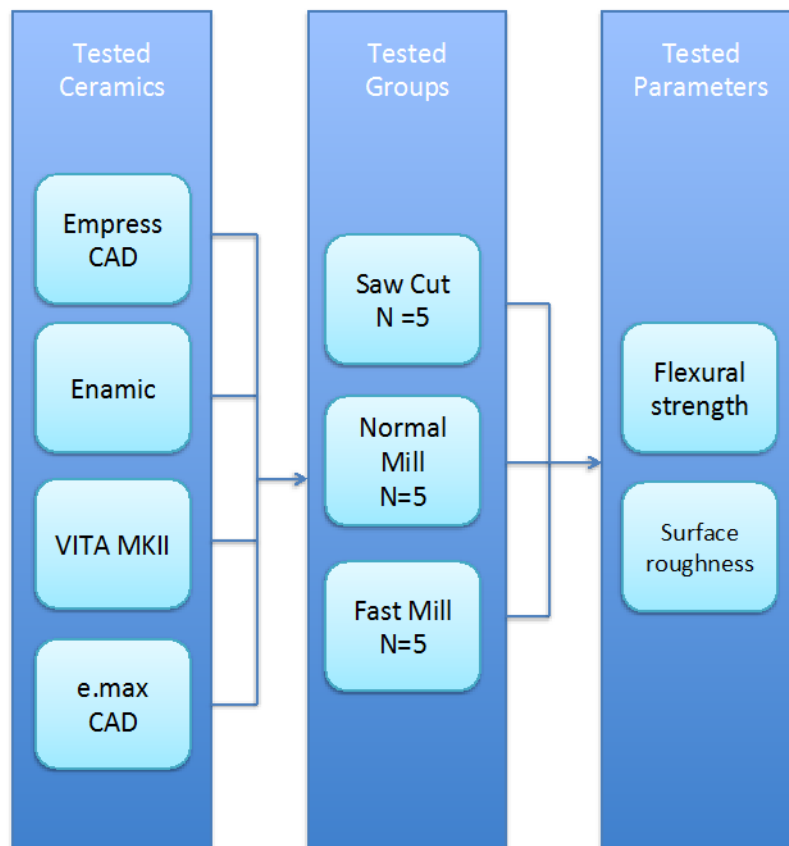


Figure 3: Outline of tested groups and test parameters

The three tested groups were as follows:

- Saw cut
- As machined:
  - Standard milling
  - Fast milling

### **2.2.1 Saw cut bars fabrication**

The bars' dimensions were chosen using the ISO standard 6872 as a reference.<sup>39</sup>

Bar Dimensions:

- Width  $w = 4.0 \text{ mm} \pm 0.2 \text{ mm}$
- Thickness  $b = 1.2 \text{ mm to } 3.0 \text{ mm} \pm 0.2 \text{ mm}$
- Length  $l = 14.0 \text{ mm}$

The blocks were sectioned using a BUHLER Isomet 5000 precision saw® (BUHLER, Lake Bluff, Illinois) (Figure4). The blocks were then placed in the sectioning machine and oriented perpendicularly to the saw. The blade used for sectioning was a low concentration diamond bade 15LC, NO. 11-4276 ( $\phi 15.2 \text{ cm} \times 0.5 \text{ mm}$ ). The sectioning was performed under running water with a blade speed of 2000 RPM and a feed rate of 8.3 mm/min. After the first set of thickness cut finished, the block was rotated 90 degrees for the second set of width cut. Finally, the bars were sectioned off to acquire desired length (Figure 5).

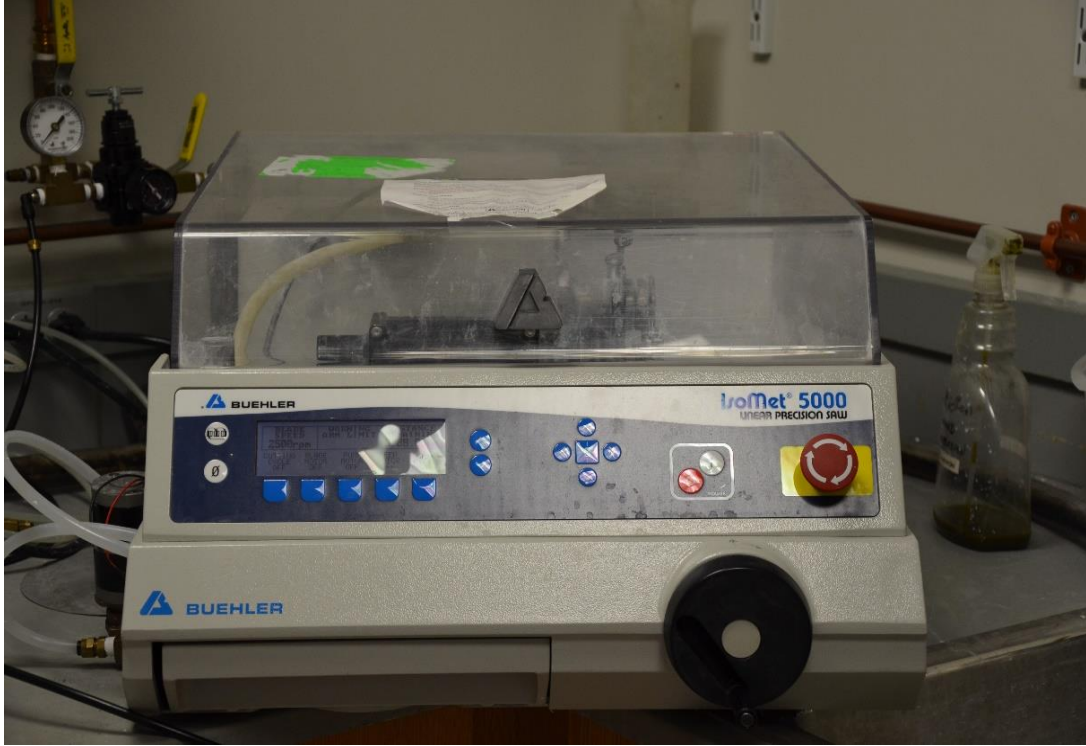


Figure 4: BUEHLER Isomet 5000 precision saw®

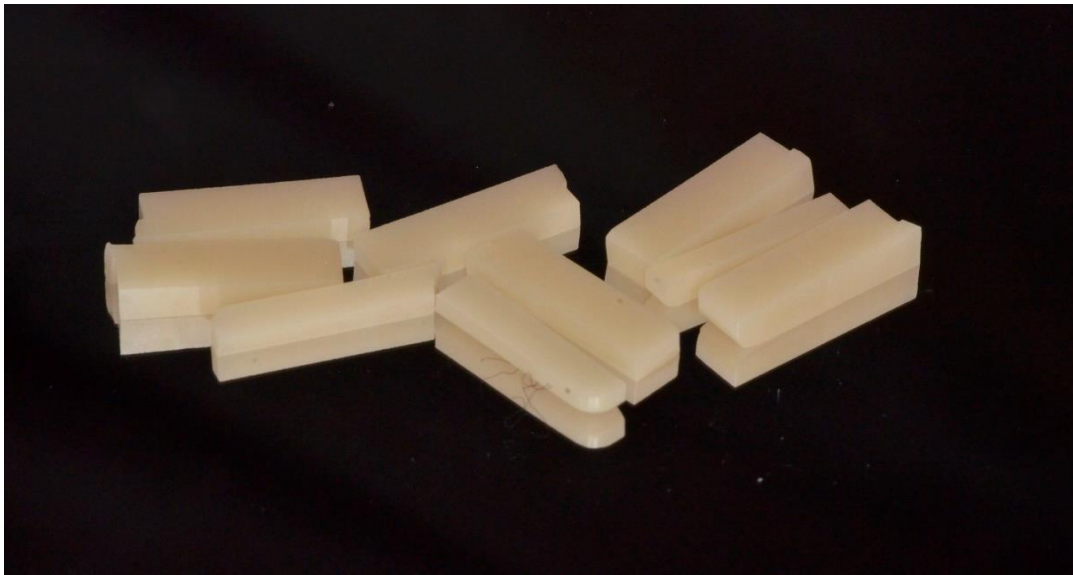


Figure 5: Sectioned Empress CAD bars

### **2.2.2 Machined bars fabrication**

The bars in the machined groups were fabricated using the CEREC MCXL (SIRONA, Charlotte, NC) milling machine, software SIRONA inLab ver. 4.2.5.78926. Using a dental typodont, the lower left side was scanned after removal of teeth # 19,20. The software was manipulated into designing a fixed partial denture framework with the mid-section being parallel and having the same dimensions as the sectioned rectangular bars (Figure 6). The burs setup that was used based on the bur guide provided by SIRONA.<sup>40</sup> The burs were changed to a new set for each specimen group. The CAD/CAM block was placed into the MC XL unit and milled with either normal or fast mill option. For e.max CAD, only normal mill option was available. Since only one bar could be produced from each block, five blocks were used for each group. After the milling process, the specimen was removed from the milling unit and sectioned off the base (Figure 7,8).

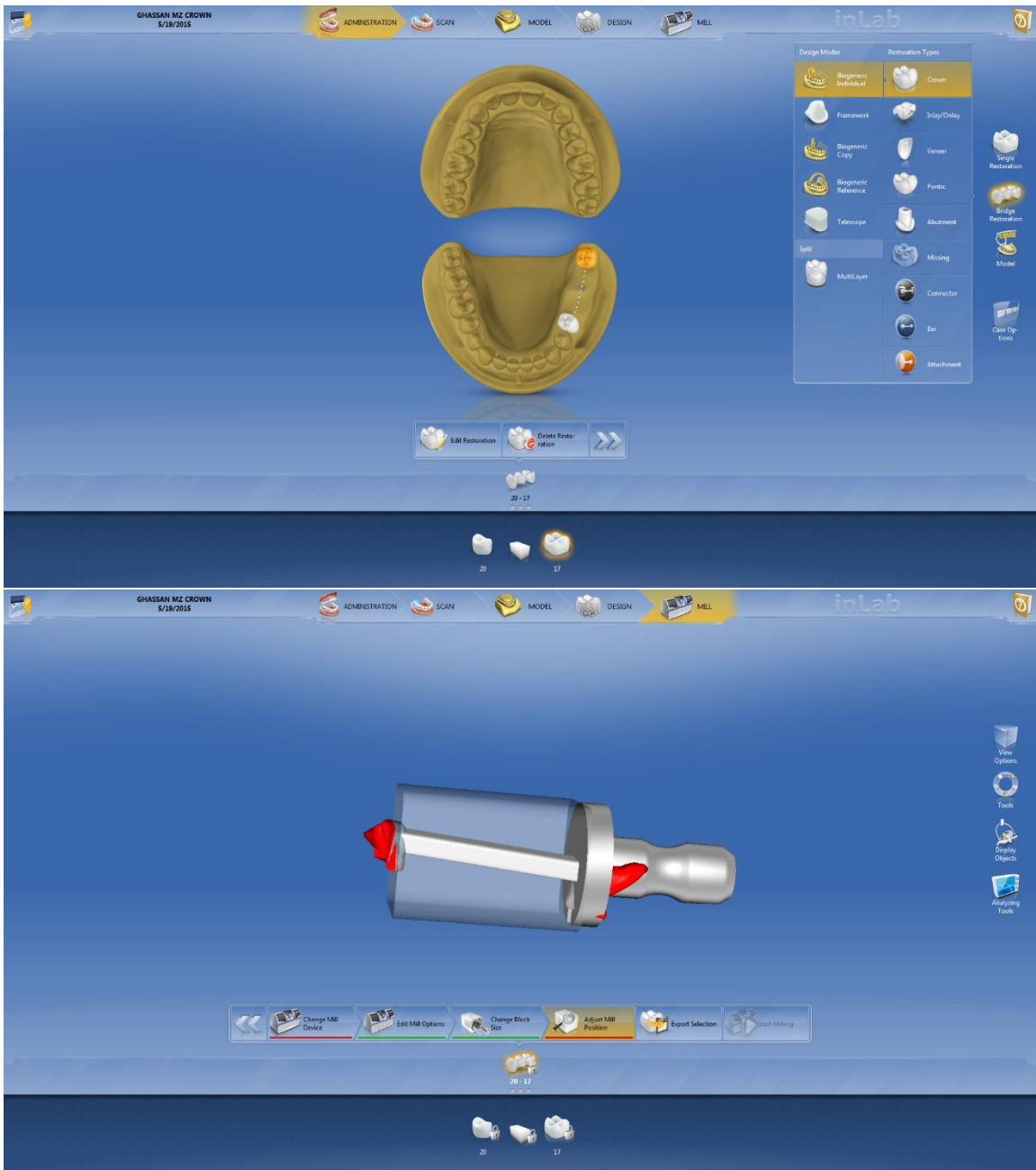


Figure 6: Image of designed bars

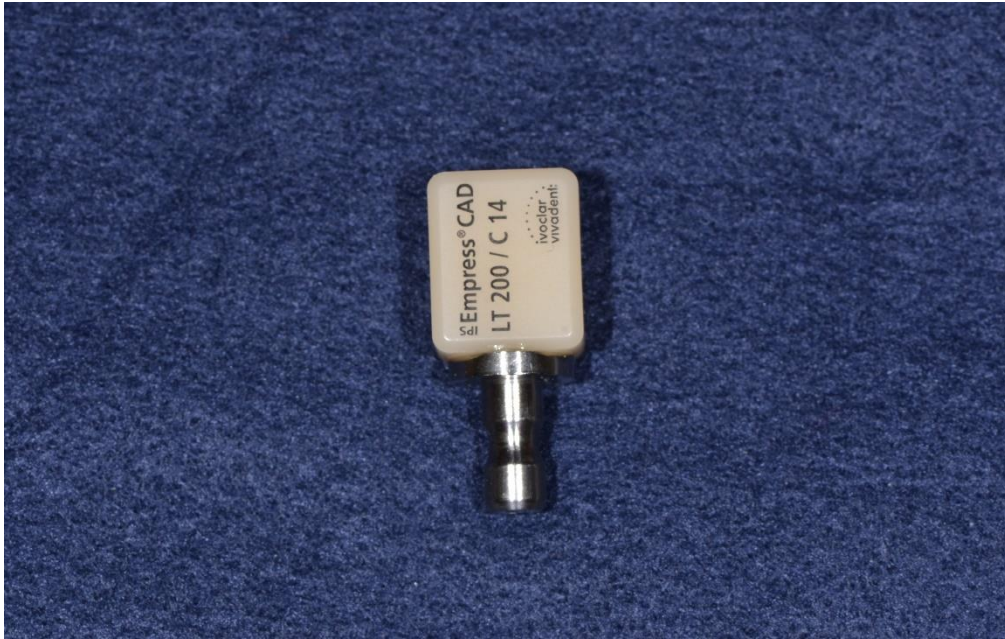


Figure 7: Empress CAD block before milling



Figure 8: Empress CAD milled bar

### 2.2.3 Specimen preparation

After fabrication of the bars, the specimens were cleaned, in water, in an ultrasonic bath for one minute to remove debris, then air-dried. To achieve final crystallization for the e.max CAD groups, the bars were placed into ceramic furnace (Programat CS- Ivoclar Vivadent, Amherst, NY) (Figure 9). The preset program #1 for crystallization was selected. The firing temperature will reach 840 °C with a holding time of 7 minutes. After firing, the bars were allowed to cool down then removed from the furnace.

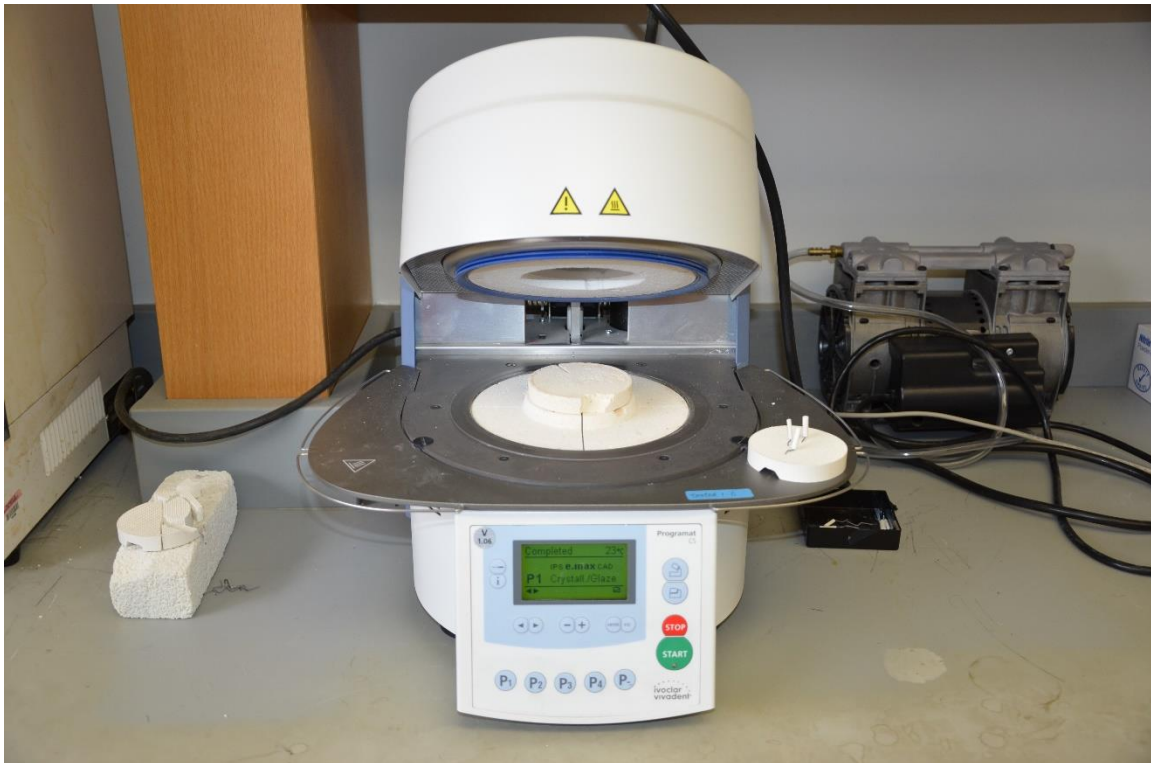


Figure 9: Programat CS ceramic furnace

The dimensions of the bars (width, and thickness) were measured and recorded using micrometer (Model No. CD-4”CS; Mitutoyo Corp., Japan). The thickness of the specimen was measured after testing with the Instron machine.

## 2.2.4 Flexural strength test

In this study, the 3-point flexural strength test was used. A universal testing machine was used for this test (Instron Model 5566A; Instron Co., Norwood, MA) (Figure 10). The bars were placed onto a 10 mm span mount. Since the bars surface was not treated, the top and bottom orientation during placement on the Instron machine was selected randomly. The specimen was aligned to be in the middle when meeting the upper pusher rod. The crosshead rate used was 0.5 mm/min with a load cell of 10 kN. Once the fixture contacted the specimen, both compressive and tensile forces were exerted, where the tensile force was on the bottom surface. Once the specimen fractured as shown in Figure 11, the failure load was recorded by the software.



Figure 10: Instron Model 5566A universal testing machine

The following equation was used for calculating the flexural strength:

$$\sigma = 3Pl / 2 wb^2$$

Where

- $\sigma$  = Flexural Strength in (Mega Pascal)
- P= The load at the fracture point (Newton)
- l= Length of the support span (Millimeter)
- w= The width of the specimen (Millimeter)
- b= The thickness of the specimen ( Millimeter)

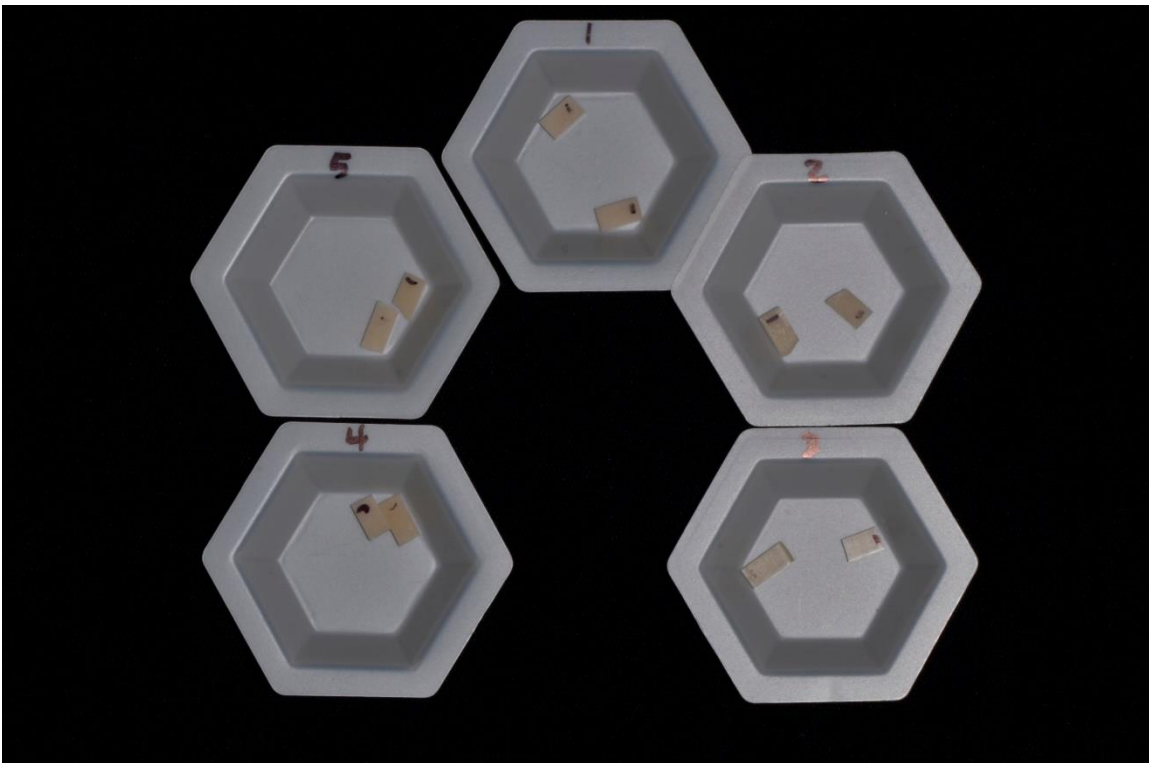


Figure 11: e.max CAD bars after performing 3-point flexural strength

### 2.2.5 Surface roughness test

The bars surface roughness was measured using a profilometer (Mitutoyo SurfTest SJ-201, Mitutoyo Corp. Japan) (Figure12). The Ra value was measured for this test. The machine

was calibrated on reference stainless steel tile with  $Ra = 3.05 \mu\text{m}$  before used for every specimen group.



Figure 12: Profilometer (Mitutoyo surf test machine model SJ-20)

The testing parameters were:

- $Ra$ = Arithmetic averaged surface roughness (Micrometers)
- Cut of length – 0.25 mm
- Number of sampling lengths- 3

The bars were placed in a previously made putty index. The profilometer was placed with the stylus contacting the specimen. Measurements were done both longitudinally and across (transverse) on the specimen. The measurements were run four times (one for each

surface) for each specimen and the mean was calculated. One specimen from each group was selected in random for imaging. The specimens were sputter coated with gold-palladium and silver paint was used to improve conductivity. When using the silver paint, the specimens were allowed to dry prior to scanning. Field emission scanning electron microscope (SU6600, Hitachi High Tech, Ltd, Tokyo, Japan) images were taken on the fracture surface of the specimen.

### Chapter 3. Results

The data for the mean flexural strength and surface roughness values for all tested groups is summarized in Tables 2, 3, 4. Figure 13 represents a graph comparing mean flexural strength to section method of the tested groups. During the milling of the last specimen of the Empress CAD fast mill group, the 12S pointed bur broke and a replacement was used to finish the milling process. No other incidents were observed during the milling. In general, e.max CAD had the highest flexural strength values for both saw cut and milled groups. The mean surface roughness for both longitudinal and transverse measurements (Ra-L, Ra-T) compared to section method for all materials are represented by Figures 14 and 15. For both Ra-L and Ra-T, the saw cut groups had lower surface roughness compared to the milled groups. Either student t test or Tukey-Kramer statistical analysis was performed to compare differences for flexural strength and surface roughness of each material.

Table 2: Saw cut groups mean flexural strength in mega Pascal and mean surface roughness in micrometers (Ra-Longitudinal), (Ra-Transverse)

Group	Saw Cut		
	Flexural Strength (MPa)	Ra-L ( $\mu\text{m}$ )	Ra-T ( $\mu\text{m}$ )
Enamic	152.12 $\pm$ 11.02	0.26 $\pm$ 0.052	0.24 $\pm$ 0.04
MKII	141 $\pm$ 8.2	0.12 $\pm$ 0.16	0.134 $\pm$ 0.14
e.max	503.8 $\pm$ 45.59	0.4 $\pm$ 0.16	0.39 $\pm$ 0.19
Empress	130.36 $\pm$ 19.89	0.12 $\pm$ 0.03	0.14 $\pm$ 0.055

Table 3: Normal mill groups mean flexural strength in mega Pascal and mean surface roughness in micrometers (Ra-Longitudinal), (Ra-Transverse)

Group	Normal Mill		
	Flexural Strength (MPa)	Ra-L ( $\mu\text{m}$ )	Ra-T ( $\mu\text{m}$ )
Enamic	135.22 $\pm$ 7.13	1.465 $\pm$ 0.24	1.259 $\pm$ 0.22
MKII	117.86 $\pm$ 12.76	1.45 $\pm$ 0.24	1.18 $\pm$ 0.16
e.max	403.94 $\pm$ 14.85	1.4 $\pm$ 0.14	1.44 $\pm$ 0.17
Empress	133.98 $\pm$ 23.2	1.26 $\pm$ 0.19	1.22 $\pm$ 0.15

Table 4: Fast mill groups' mean flexural strength in mega Pascal and mean surface roughness in micro meters (Ra-Longitudinal), (Ra-Transverse)

Group	Fast Mill		
	Flexural Strength (Mpa)	Ra-L ( $\mu\text{m}$ )	Ra-T ( $\mu\text{m}$ )
Enamic	147.61 $\pm$ 5.7	1.38 $\pm$ 0.23	1.16 $\pm$ 0.131
MKII	114.56 $\pm$ 7	1.41 $\pm$ 0.29	1.3 $\pm$ 0.18
e.max	/	/	/
Empress	116.67 $\pm$ 10.2	1.37 $\pm$ 0.27	1.192 $\pm$ 0.21

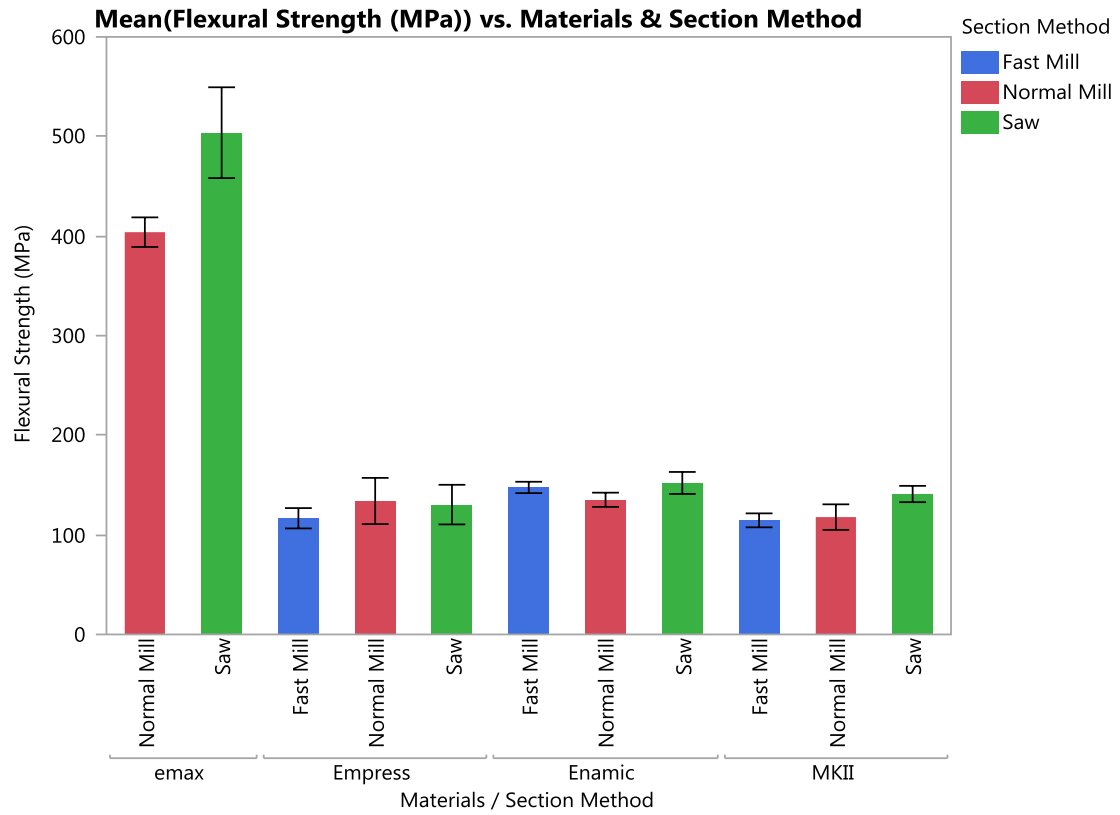


Figure 13: Bar graph of flexural strength (MPa) vs. Section methods (Saw cut, Normal mill, Fast Mill) for all tested materials

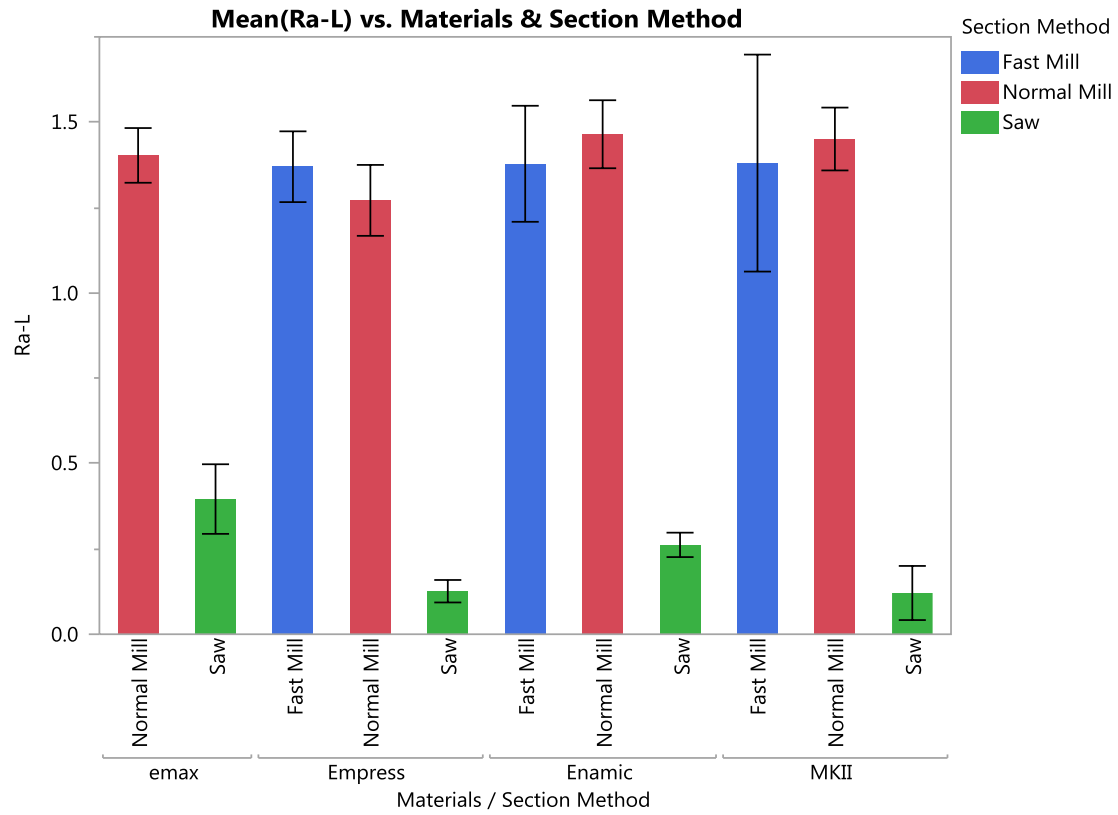


Figure 14: Bar graph of mean surface roughness ( $\mu\text{m}$ ) Ra-Longitudinal vs. Section method (Saw cut, Normal mill, Fast Mill) for all tested materials

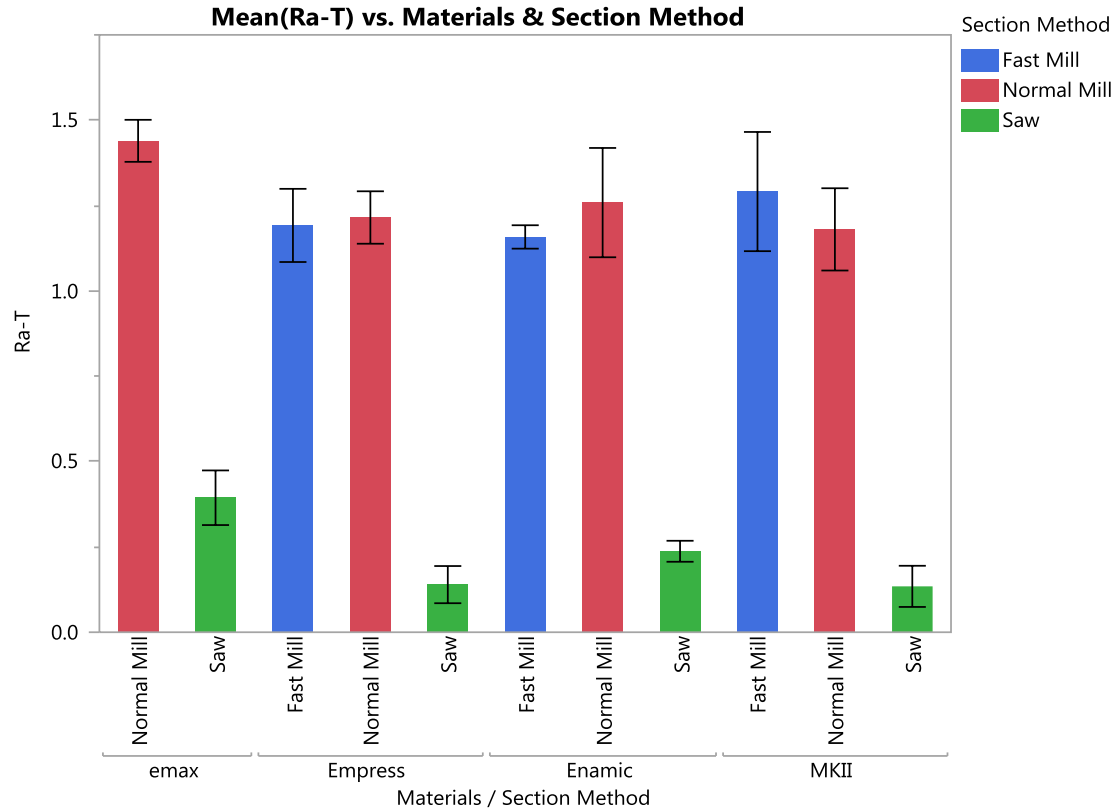


Figure 15: Graph of mean surface roughness ( $\mu\text{m}$ ) Ra-transvers vs. Section method (Saw cut, Normal mill, Fast Mill) for all tested materials

### 3.1 e.max CAD

#### 3.1.1 Flexural strength

Saw cut e.max bars showed flexural strength of  $503.8 \pm 45.59$  MPa; surface roughness of  $0.4 \pm 0.16$   $\mu\text{m}$  in longitudinal direction and  $0.39 \pm 0.19$   $\mu\text{m}$  in transverse direction. The normal mill group's mean flexural strength was  $403.94 \pm 14.85$  MPa and the surface roughness was  $1.4 \pm 0.14$   $\mu\text{m}$  longitudinal and  $1.44 \pm 0.17$   $\mu\text{m}$  transverse. Statistical analysis showed that the saw cut group was significantly higher than the milled group ( $p = 0.0016$ ) (Table 6 and Figure 16). Furthermore, the surface roughness for the saw cut group was significantly lower than the milled group both for longitudinal and transverse

directions ( $p < 0.0001$ ) (Table 7, 8) (Figure 17, 18). Figure 19 shows a plot of bivariate fit for the flexural strength against Ra-L for e.max CAD. The R-squared value was 0.67, which indicates a strong inverse relationship between the flexural strength and Ra-L.

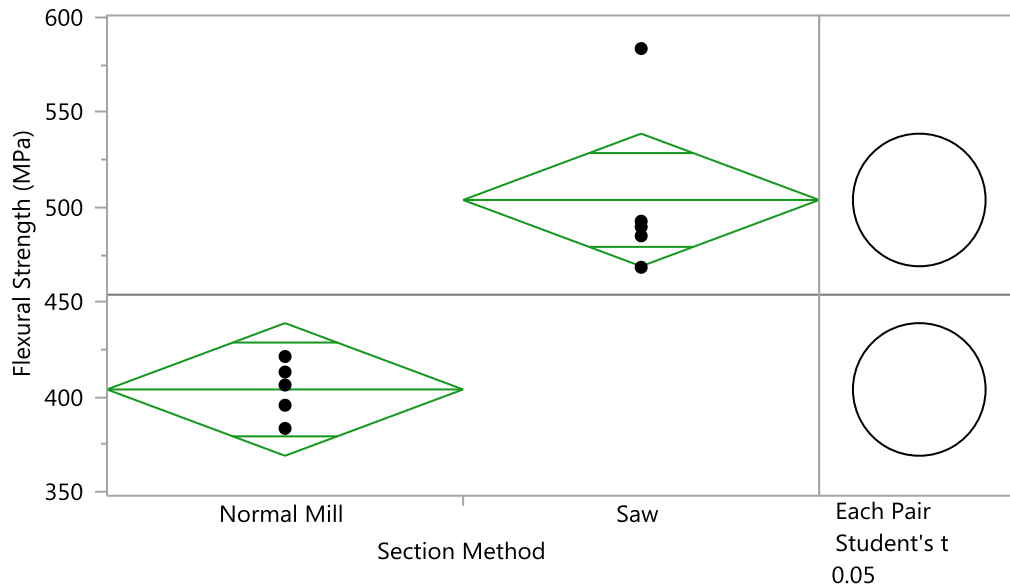


Figure 16: One-way analysis of flexural strength (MPa) by section method for e.max

Table 5: One-way Anova summary of fit for flexural strength of e.max CAD

<b>Rsquare</b>	0.730605
<b>Adj Rsquare</b>	0.696931
<b>Root Mean Square Error</b>	33.90716
<b>Mean of Response</b>	453.86
<b>Observations (or Sum Wgts)</b>	10

Table 6: Analysis of variance for flexural strength of e.max CAD

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Section Method	1	24944.031	24944.0	21.6962	0.0016*
Error	8	9197.562	1149.7		
C. Total	9	34141.593			

### 3.1.2 Surface roughness

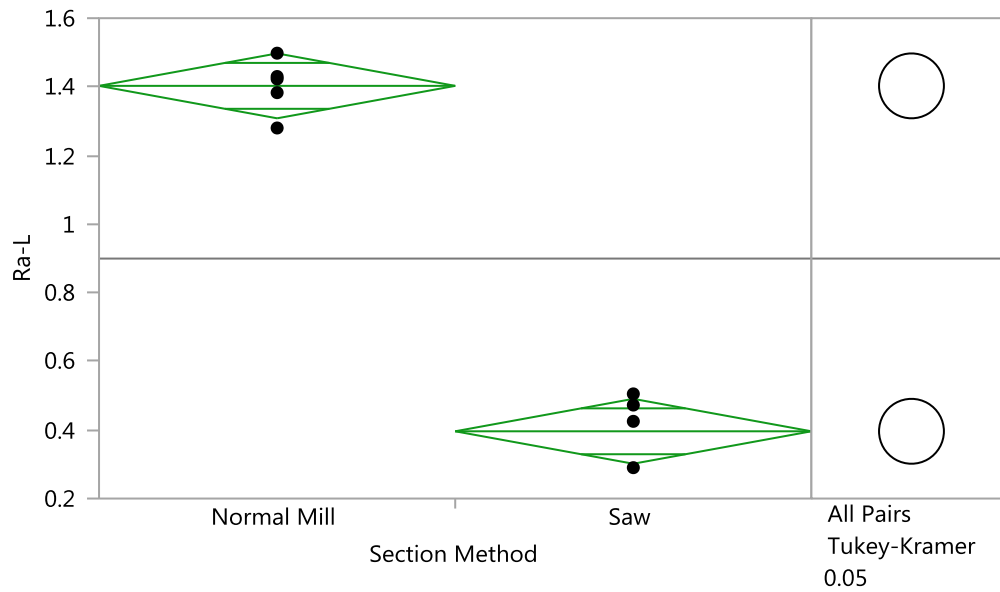


Figure 17: One-way analysis of Ra-L ( $\mu\text{m}$ ) by section method for e.max CAD

Table 7: Analysis of variance for Ra-L of e.max CAD

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Section Method	1	2.5341156	2.53412	301.3876	<.0001*
Error	8	0.0672653	0.00841		
C. Total	9	2.6013809			

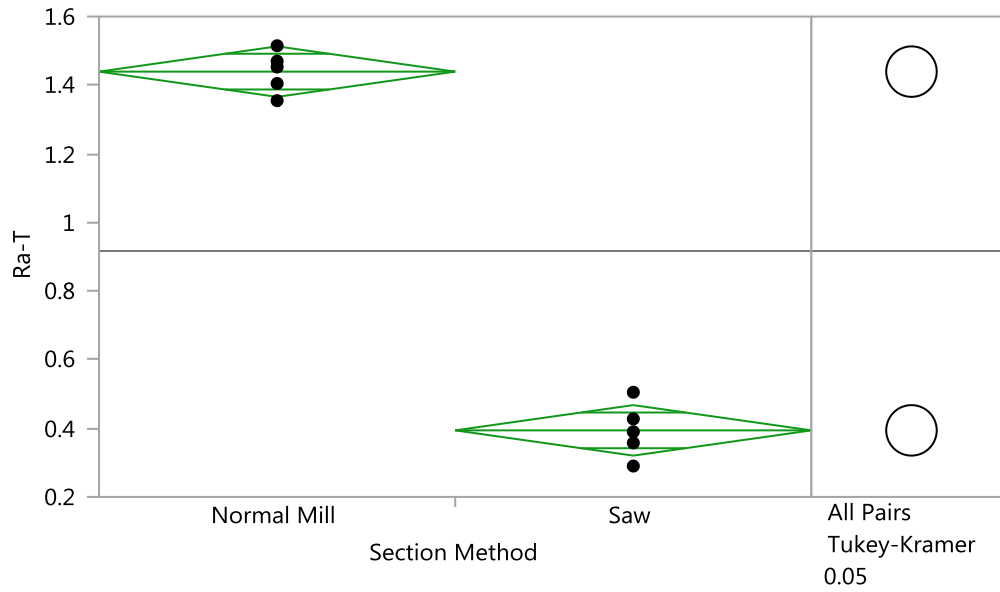


Figure 18: One-way analysis of Ra-T ( $\mu\text{m}$ ) by section method for e.max CAD

Table 8: Analysis of variance for Ra-T of e.max CAD

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Section Method	1	2.7331984	2.73320	536.5696	<.0001*
Error	8	0.0407507	0.00509		
C. Total	9	2.7739491			

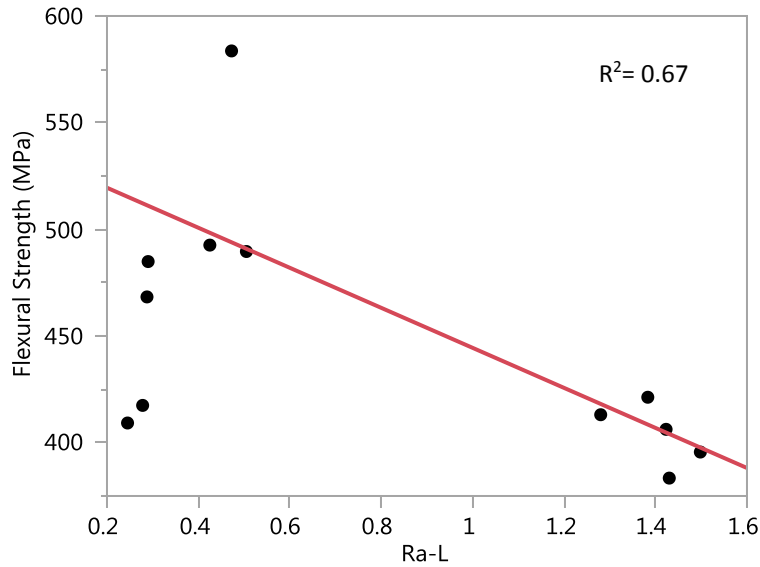


Figure 19: Bivariate Fit of Flexural Strength (MPa) By Ra-L for e.max CAD

### 3.1.3 Microstructural analysis

Figures 20, 21, and 22 show the SEM images of fracture site for the saw cut and milled group where the arrows pointing to surface defects. In Figure 20, it is observed that the saw cut bars had straighter edges compared to the milled bars. The fracture started from the tension side. It is observed from the close up images in Figures 21, and 22 that the milled group had higher number edge chipping that are also larger size compared to the saw cut group.

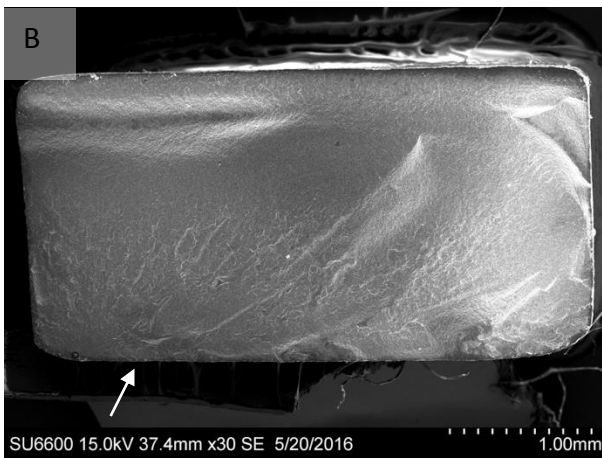
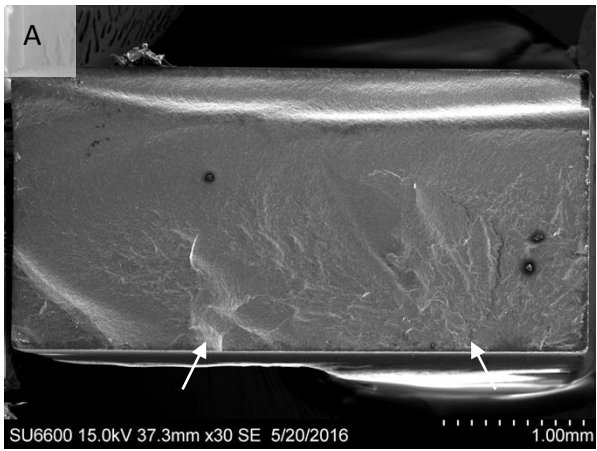


Figure 20: SEM images of fracture site for e.max CAD: A- Saw cut, B- Normal mill.

The arrows indicate fracture starting point.

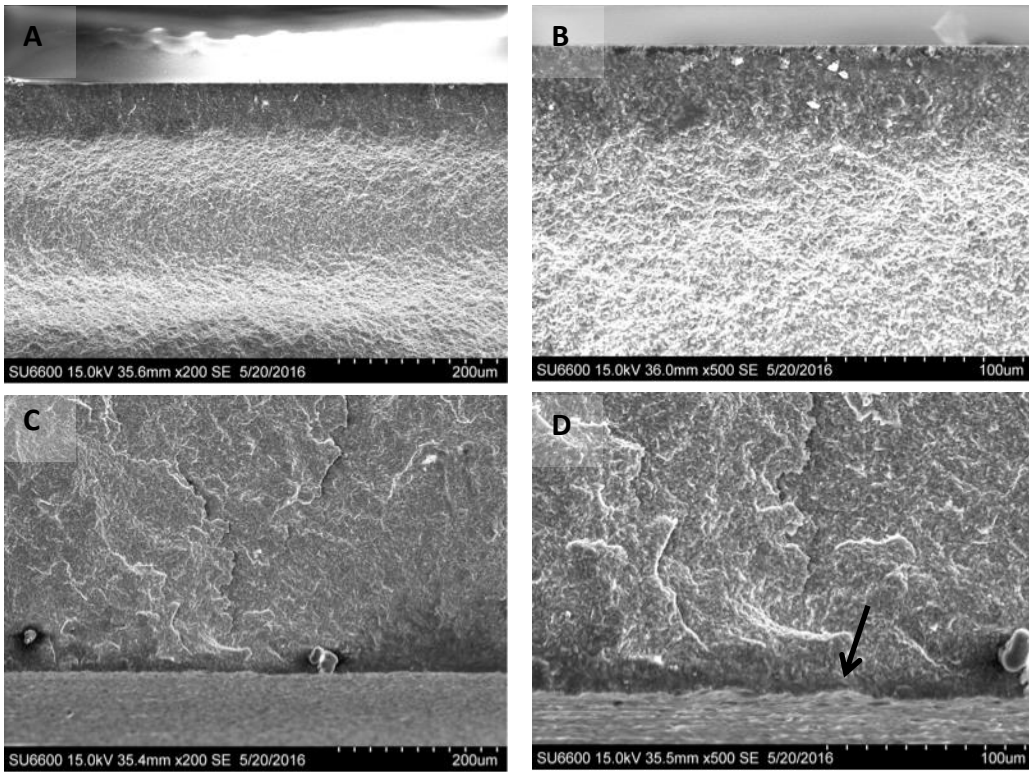


Figure 21: SEM images of fracture site for e.max CAD saw cut group: A, B compression side of fracture site. C, D tension side. Arrow indicates a possible chipping damage.

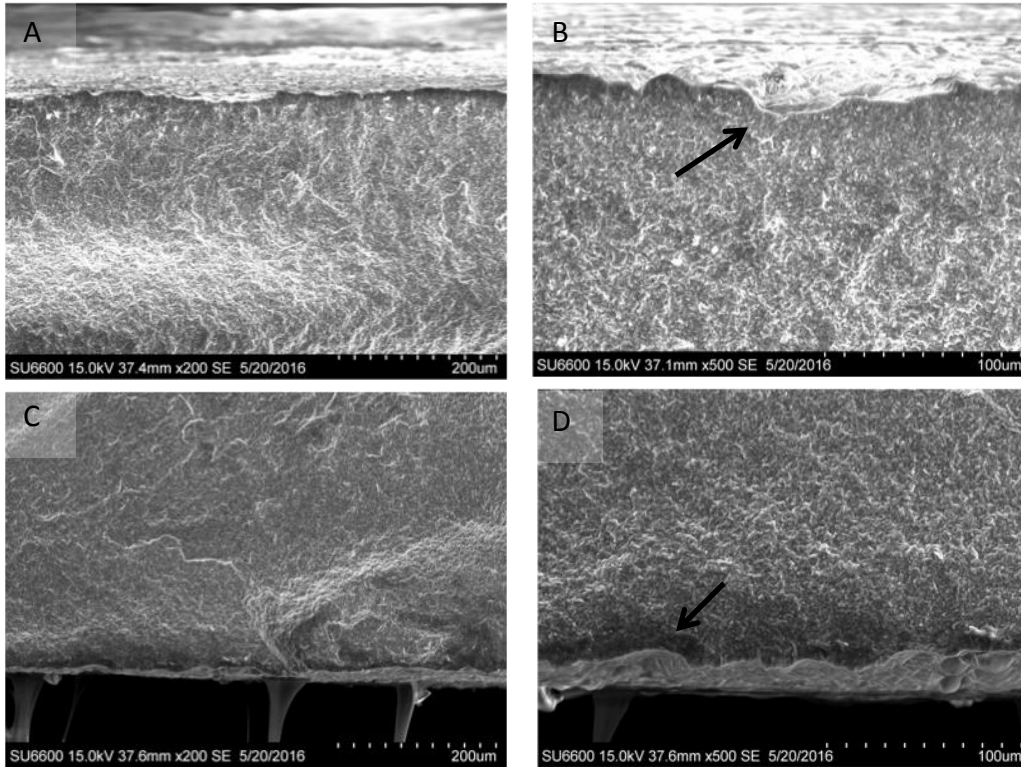


Figure 22: SEM image of fracture site for e.max CAD milled group: A, B compression side of fracture site. C, D tension side. Arrows indicate possible chipping damage.

## 3.2 Empress CAD

### 3.2.1 Flexural Strength

The saw cut group had mean flexural strength of  $130.36 \pm 19.89$  MPa, the normal mill group's flexural strength was  $133.98 \pm 23.2$  MPa and the fast mill group's flexural strength was  $116.67 \pm 10.2$  MPa. The measured surface roughness for the saw cut group  $0.12 \pm 0.03$   $\mu\text{m}$  longitudinal and  $0.14 \pm 0.06$   $\mu\text{m}$  transverse. For the normal milled group, the surface roughness was  $1.26 \pm 0.19$   $\mu\text{m}$  longitudinal  $1.22 \pm 0.15$   $\mu\text{m}$  transverse, and for the normal

mill group  $1.37 \pm 0.27 \mu\text{m}$  longitudinal and  $1.19 \pm 0.21 \mu\text{m}$  transverse. There was no significant difference between the flexural strength of all three groups ( $P > 0.05$ ) (Figure 23) (Table 10). Power analysis was done and the least significant number (LSN) was calculated to be 40.4. However, the surface roughness for Empress CAD saw cut group was significantly lower in both directions compared to the milled groups. There was no significant difference in the surface roughness of the normal mill and fast mill groups in both longitudinal and transverse directions (Figure 24, 25) (Table 12, 14).

The graph in Figure 26 shows the bivariate fit for Empress CAD. From the slope and the R-squared value of 0.01 it is observed that the correlation between the flexural strength and the surface roughness is weak for Empress CAD.

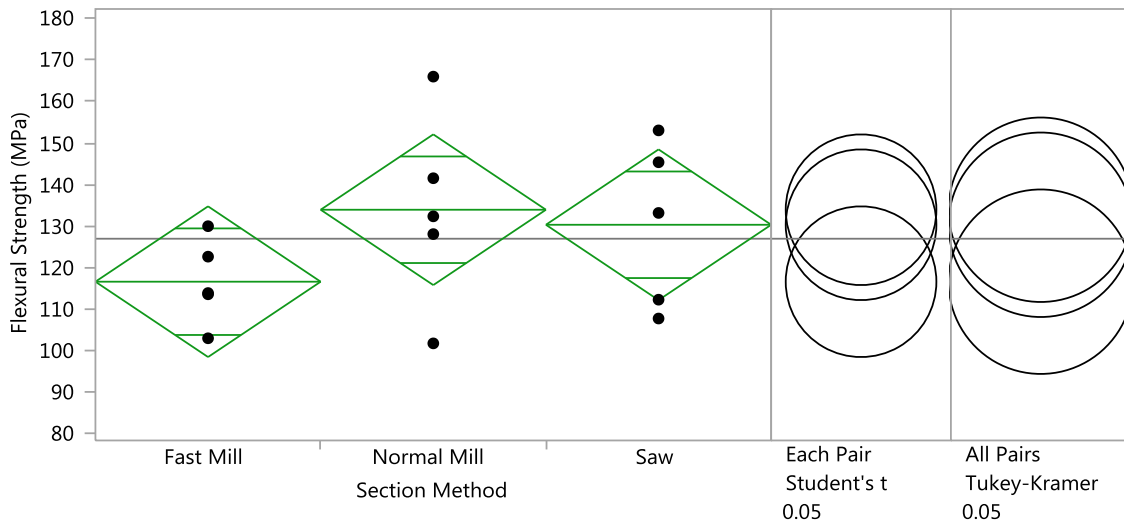
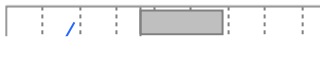




Figure 23: One-way analysis of flexural strength (MPa) by section method for Empress CAD

Table 9: Connecting Letters Report for flexural strength for flexural strength of Empress CAD

Level		Mean
Normal Mill	A	133.98000
Saw	A	130.36520
Fast Mill	A	116.66960

Table 10: Tukey test ordered differences report for flexural strength of Empress CAD

Level	Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value	
Normal Mill	Fast Mill	17.31040	11.76537	-14.0768	48.69755	0.3382	
Saw	Fast Mill	13.69560	11.76537	-17.6916	45.08275	0.4955	
Normal Mill	Saw	3.61480	11.76537	-27.7724	35.00195	0.9495	

### 3.2.2 Surface roughness

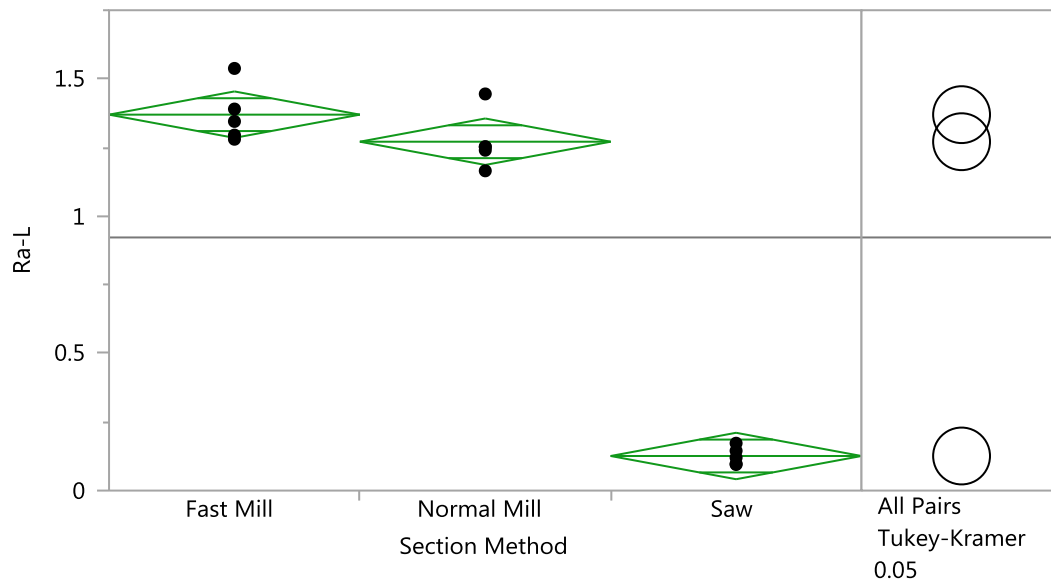





Figure 24: One-way analysis of Ra-L ( $\mu\text{m}$ ) by section method for Empress CAD

Table 11: Connecting Letters Report for Empress CAD Ra-L

Level			Mean
Fast Mill	A		1.3696000
Normal Mill	A		1.2710000
Saw		B	0.1260000

\*Levels not connected by same letter are significantly different

Table 12: Ordered Differences report for Empress CAD Ra-L

Level	Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value	
Fast Mill	Saw	1.243600	0.0549130	1.09711	1.390095	<.0001*	
Normal Mill	Saw	1.145000	0.0549130	0.99851	1.291495	<.0001*	
Fast Mill	Normal Mill	0.098600	0.0549130	-0.04789	0.245095	0.2125	

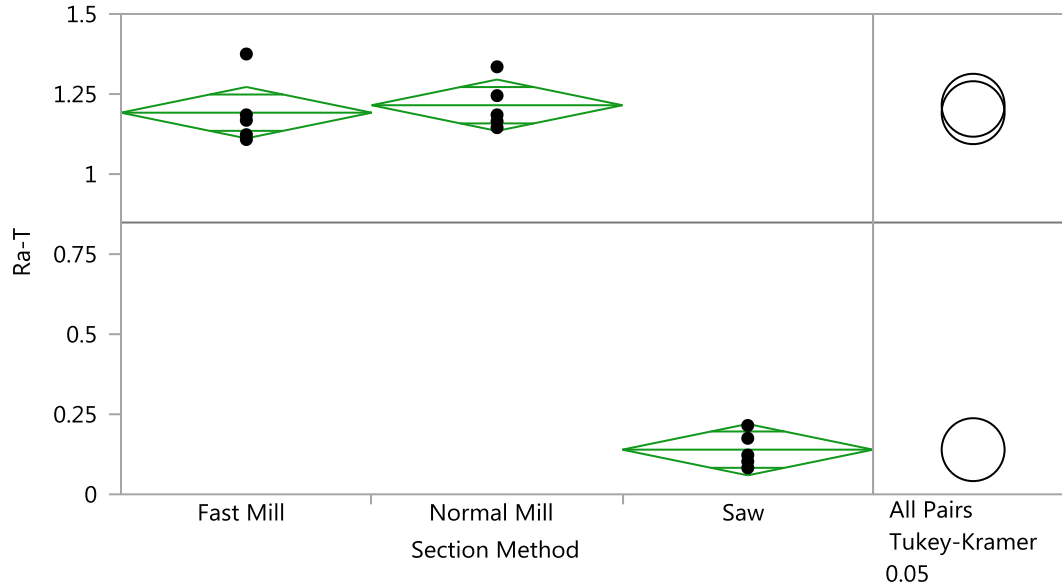


Figure 25: One-way analysis of Ra-T ( $\mu\text{m}$ ) by section method for Empress CAD

Table 13: Connecting Letters Report for Empress CAD Ra-T

Level			Mean
Normal Mill	A		1.2150000
Fast Mill	A		1.1918000
Saw		B	0.1395000

Table 14: Ordered Differences report for Empress CAD Ra-T

Level	Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Normal Mill	Saw	1.075500	0.0520891	0.936539	1.214461	<.0001*
Fast Mill	Saw	1.052300	0.0520891	0.913339	1.191261	<.0001*
Normal Mill	Fast Mill	0.023200	0.0520891	-0.11576	0.162161	0.8973

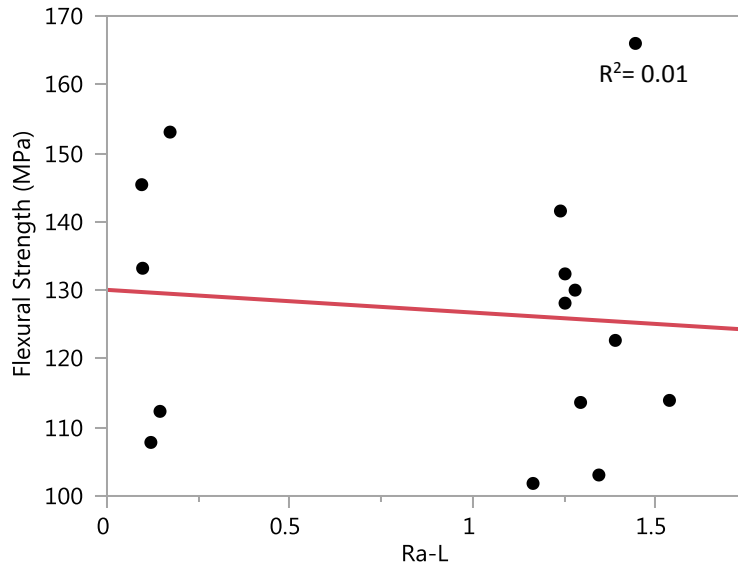


Figure 26: Bivariate Fit of Flexural Strength (MPa) By Ra-L for Empress

### 3.2.3 Microstructural analysis

Figures 27-30 show the fracture site for the Empress CAD groups. In Figure 27 it is observed that the milled bars had more rounded edges compared to the saw cut bar. The fracture point started from the tension side. The saw cut bar fractured a little off center, while both milled bars the fracture started in the middle. The higher magnification on Figure 28 show edge chipping on the compression side. However, the rest of the surface was smooth. For the milled bars (Figure 29,30) multiple edge chips were observed on both compression and tension sides.

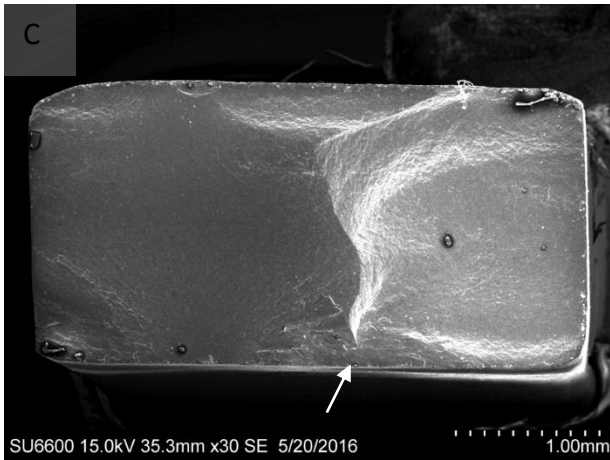
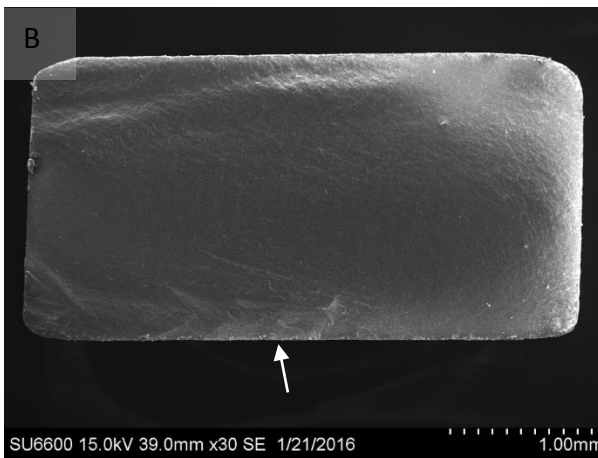
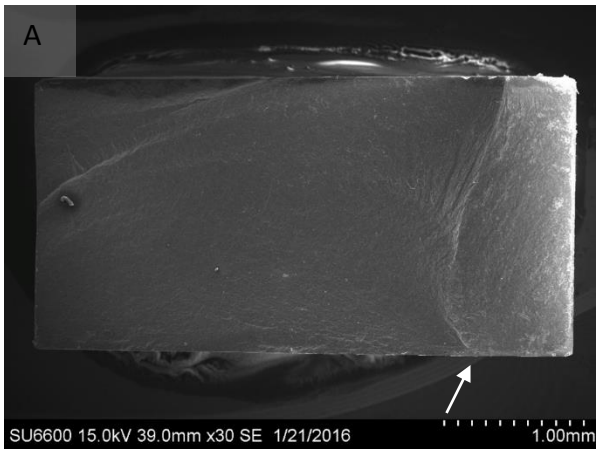


Figure 27: SEM image of fracture site for Empress CAD: A- Saw cut, B- Normal mill, C- Fast mill. The arrows indicate fracture starting point.

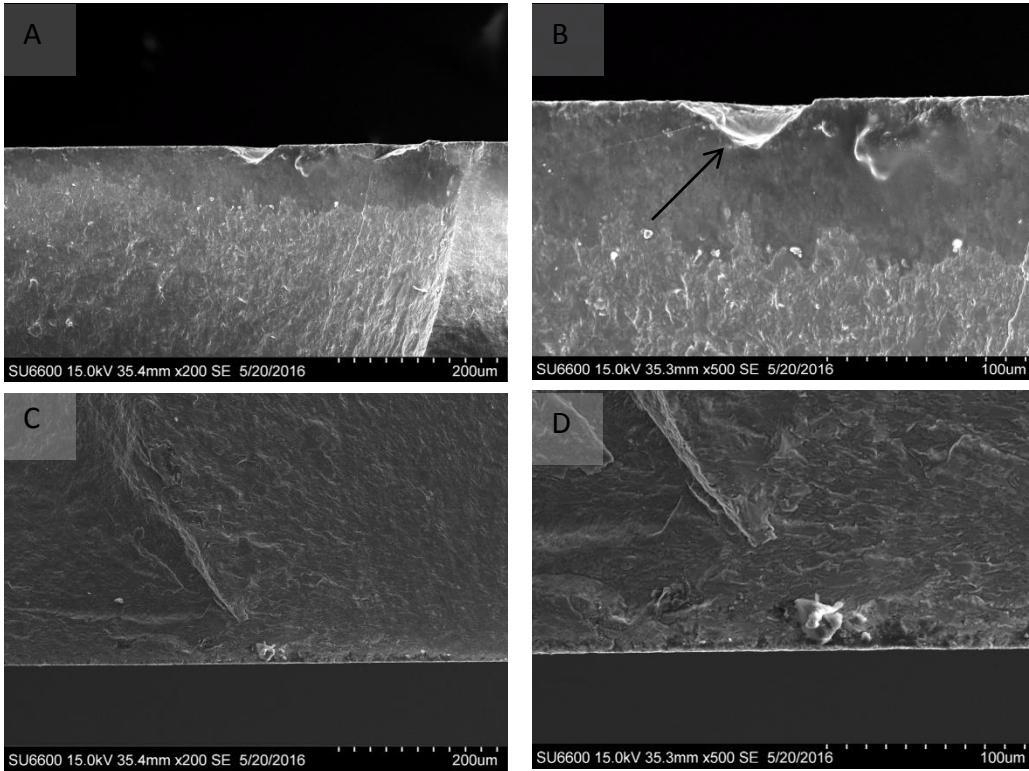


Figure 28: SEM image of fracture site for Empress CAD saw cut group: A, B compression side of fracture site. C, D tension side. Arrow indicates possible chipping damage.

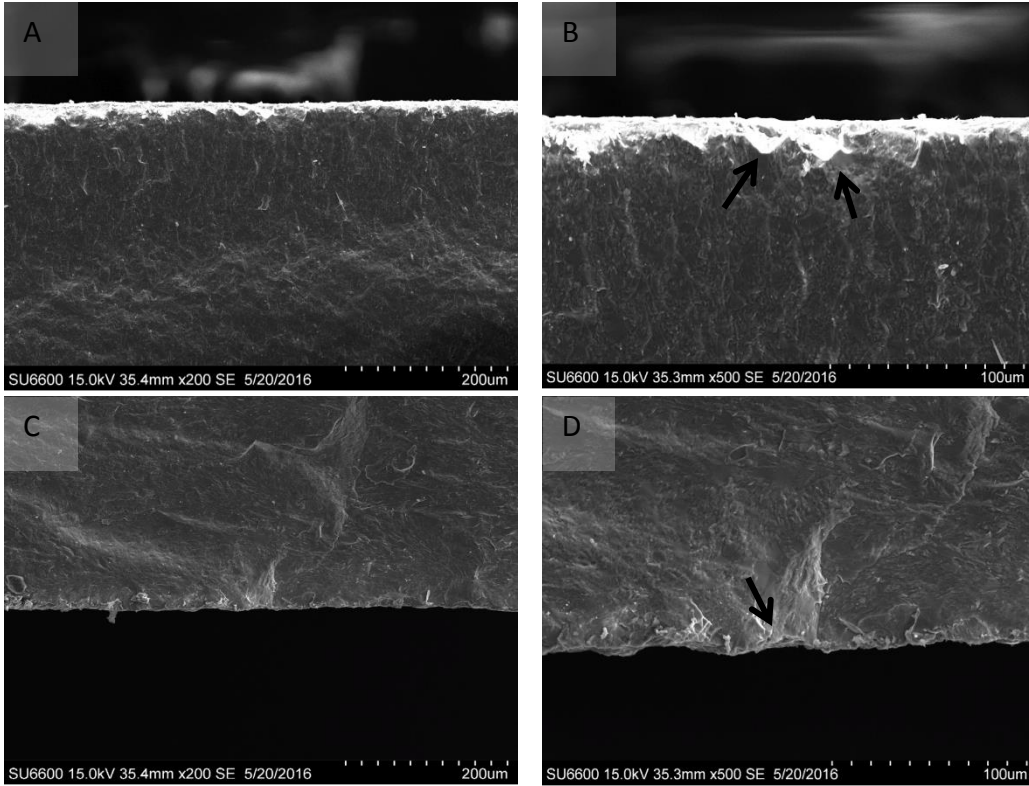


Figure 29: SEM image of fracture site for Empress CAD normal mill group: A, B compression side of fracture site. C, D tension side. Arrows indicate possible chipping damage.

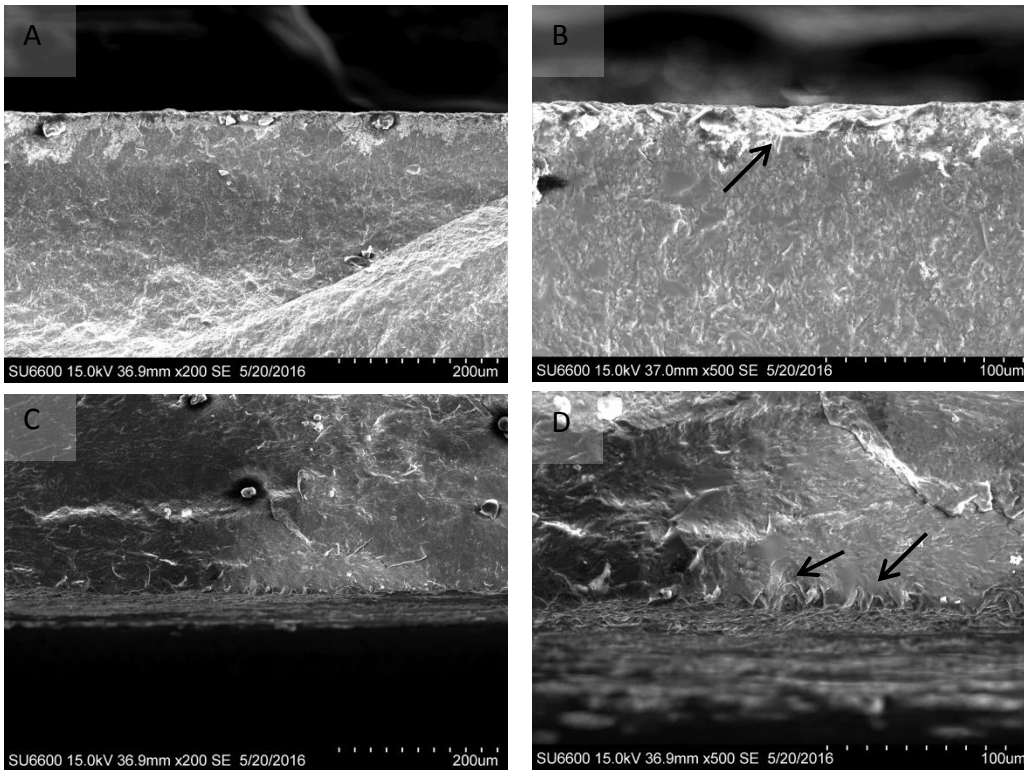


Figure 30: SEM image of fracture site for Empress CAD fast mill group: A, B compression side of fracture site. C, D tension side. Arrows indicate possible chipping damage.

### 3.3 Enamic

#### 3.3.1 Flexural strength

The flexural strength for the Enamic saw cut group was  $152.12 \pm 11.02$  MPa, while the value for the normal mill group was  $135.22 \pm 7.13$  MPa and the fast mill group  $147.61 \pm 5.7$  MPa. The surface roughness measured for the saw cut group  $0.26 \pm 0.052$   $\mu\text{m}$  longitudinal  $0.24 \pm 0.04$   $\mu\text{m}$  transverse. For the normal mill group, the surface roughness

was  $1.47 \pm 0.24 \mu\text{m}$  longitudinal and  $1.26 \pm 0.22 \mu\text{m}$  transverse, while for the fast mill group the surface roughness measurement was  $1.38 \pm 0.23 \mu\text{m}$  longitudinal and  $1.16 \pm 0.131 \mu\text{m}$  transverse. The saw cut group had significantly higher flexural strength compared to the normal mill group when using the Tukey test ( $P = 0.0183$ ) but not different from the fast mill group ( $P = 0.6735$ ) (Figure 31) (Table 16). The power analysis for the Enamic for the least significant number was 11.6. The surface roughness for saw cut group was significantly less than the normal and fast mill groups for both longitudinal and transverse measurements ( $P < 0001$ ). However, there was no significant difference in the surface roughness between the milled groups ( $P > 0.05$ ) on both measured planes (Figure 32, 33) (Table 18, 20).

The bivariate Fit of plot shown in Figure 34 show the inverse relationship between the flexural strength and the Ra-L. The R-squared value is 0.28, indicating a weaker correlation between the flexural strength and Ra-L compared to e.max CAD.

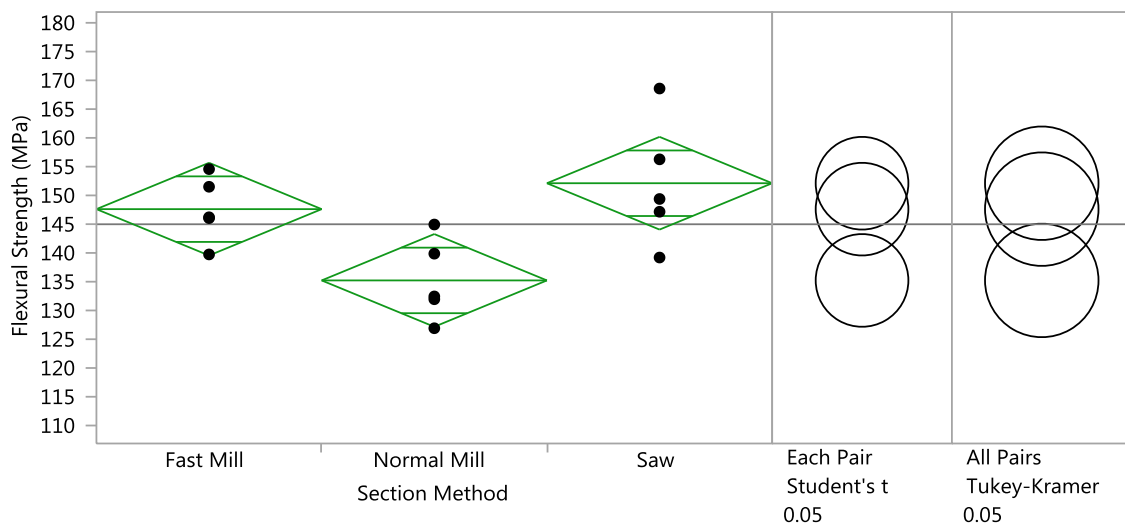


Figure 31: One-way Analysis of flexural strength (MPa) by section method for Enamic

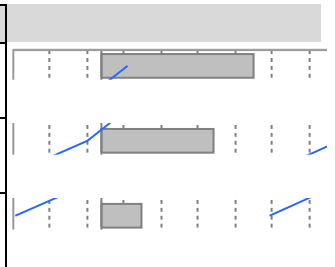
Table 15: Connecting Letters Report for flexural strength of Enamic

Level			Mean
Saw	A		152.11800
Fast Mill	A	B	147.61200
Normal Mill		B	135.22200

\*Levels not connected by same letter are significantly different

Table 16: Ordered Differences Report for flexural strength of Enamic

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Saw	Normal Mill	16.89600	5.230361	2.94267	30.84933	0.0183*
Fast Mill	Normal Mill	12.39000	5.230361	-1.56333	26.34333	0.0840
Saw	Fast Mill	4.50600	5.230361	-9.44733	18.45933	0.6735



### 3.3.2 Surface roughness

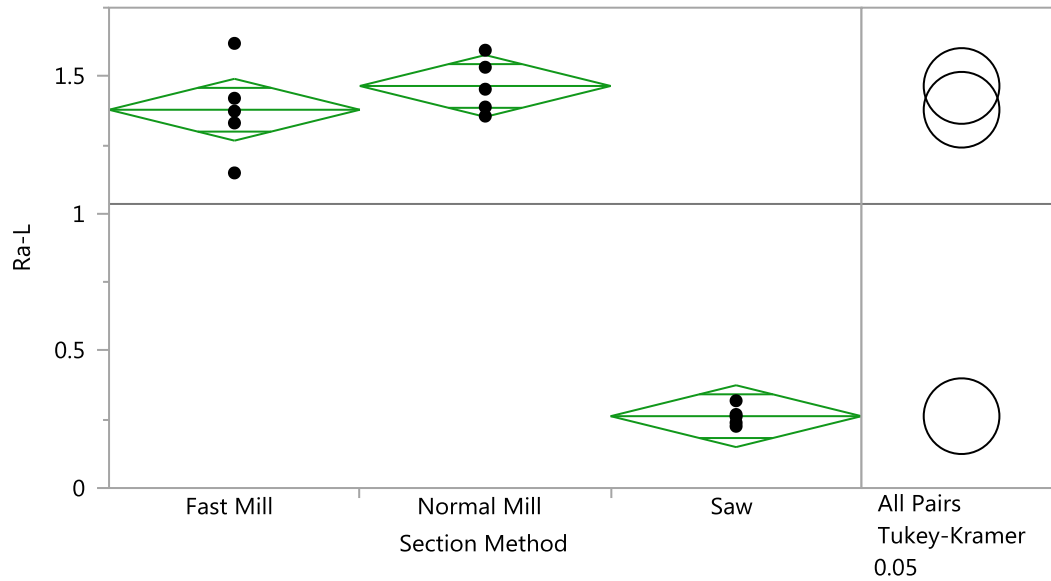


Figure 32: One-way analysis of Ra-L ( $\mu\text{m}$ ) by section method for Enamic

Table 17: Connecting Letters Report for Enamic CAD Ra-L

Level			Mean
Normal Mill	A		1.4648000
Fast Mill	A		1.3782000
Saw		B	0.2618000

\*Levels not connected by same letter are significantly different

Table 18: Ordered Differences report for Enamic Ra-L

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value	
Normal Mill	Saw	1.203000	0.0731151	1.00795	1.398053	<.0001*	
Fast Mill	Saw	1.116400	0.0731151	0.92135	1.311453	<.0001*	
Normal Mill	Fast Mill	0.086600	0.0731151	-0.10845	0.281653	0.4841	

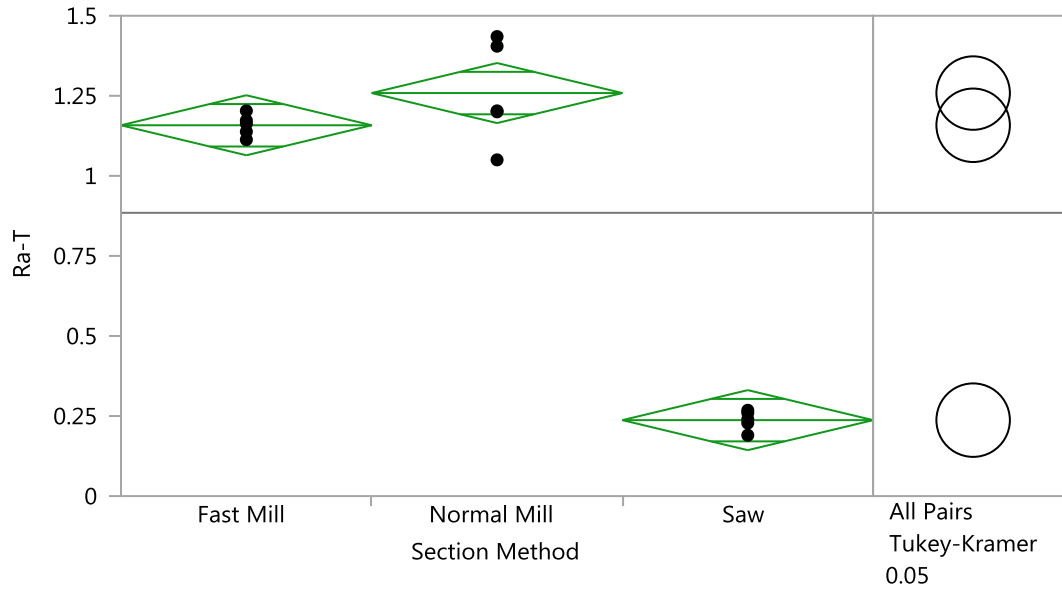


Figure 33: One-way analysis of Ra-T (µm) by section method for Enamic

Table 19: Connecting Letters Report for Enamic CAD Ra-T

Level			Mean
Normal Mill	A		1.2586000
Fast Mill	A		1.1580000
Saw		B	0.2372000

\*Levels not connected by same letter are significantly different

Table 20: Ordered Differences report for Enamic Ra-T

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Normal Mill	Saw	1.021400	0.0608490	0.859070	1.183730	<.0001*
Fast Mill	Saw	0.920800	0.0608490	0.758470	1.083130	<.0001*
Normal Mill	Fast Mill	0.100600	0.0608490	-0.061730	0.262930	0.2623

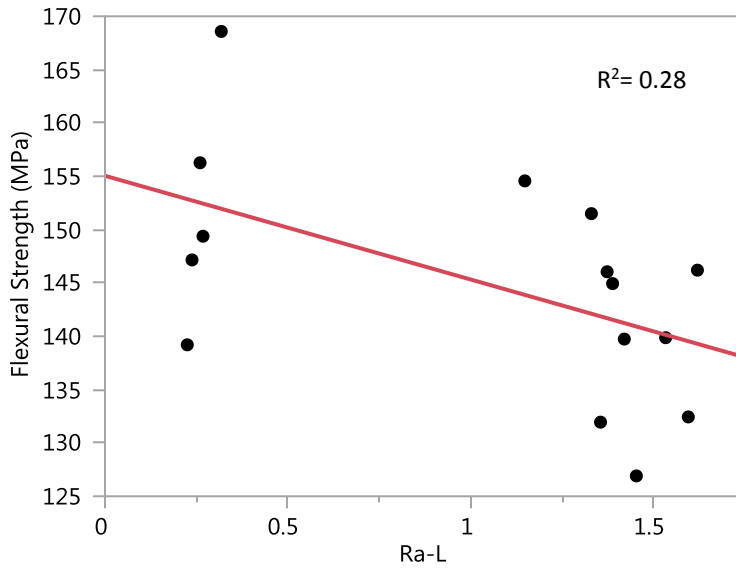


Figure 34: Bivariate Fit of Flexural Strength (MPa) By Ra-L for Enamic

### 3.3.3 Microstructural analysis

SEM images in Figures 35-38 show the fracture site of the Enamic groups. Similar to the e.max CAD and Empress CAD, in Figure 35, it is observed that the saw cut bar has straighter edges compared to the milled bars. The fractures were all initiated in the tension

side close the middle. In Figure 36 it is observed that the number and size of the edge chips is small compared to both milled groups (Figure 37,38).

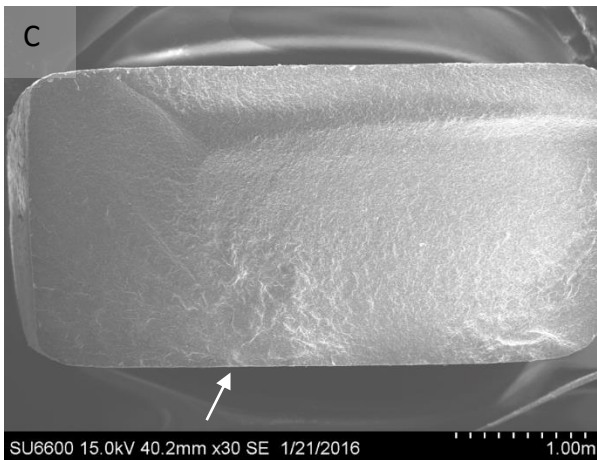
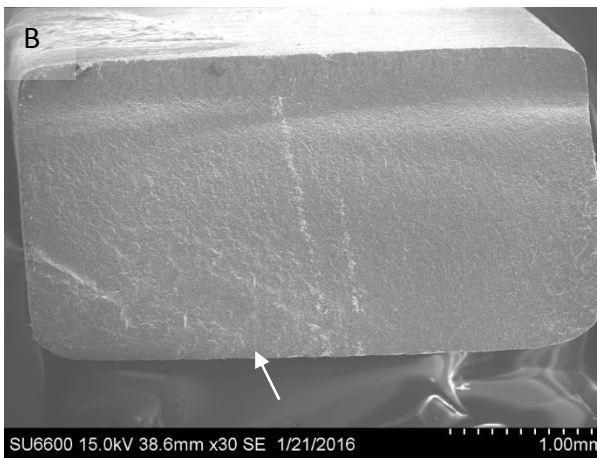
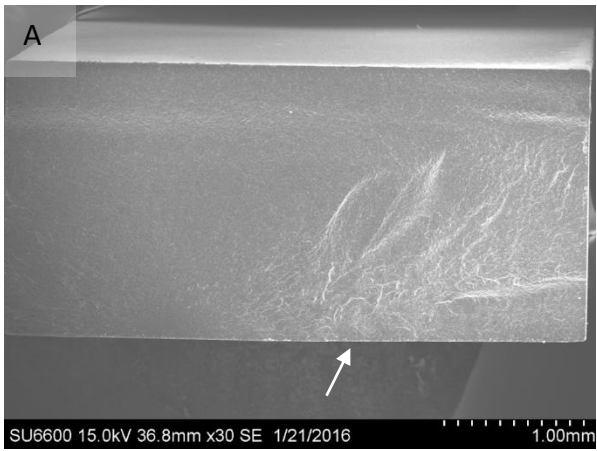


Figure 35: SEM image of fracture site for Vita Enamic CAD: A- Saw cut, B- Normal mill, C- Fast mill. The arrows indicate fracture starting point.

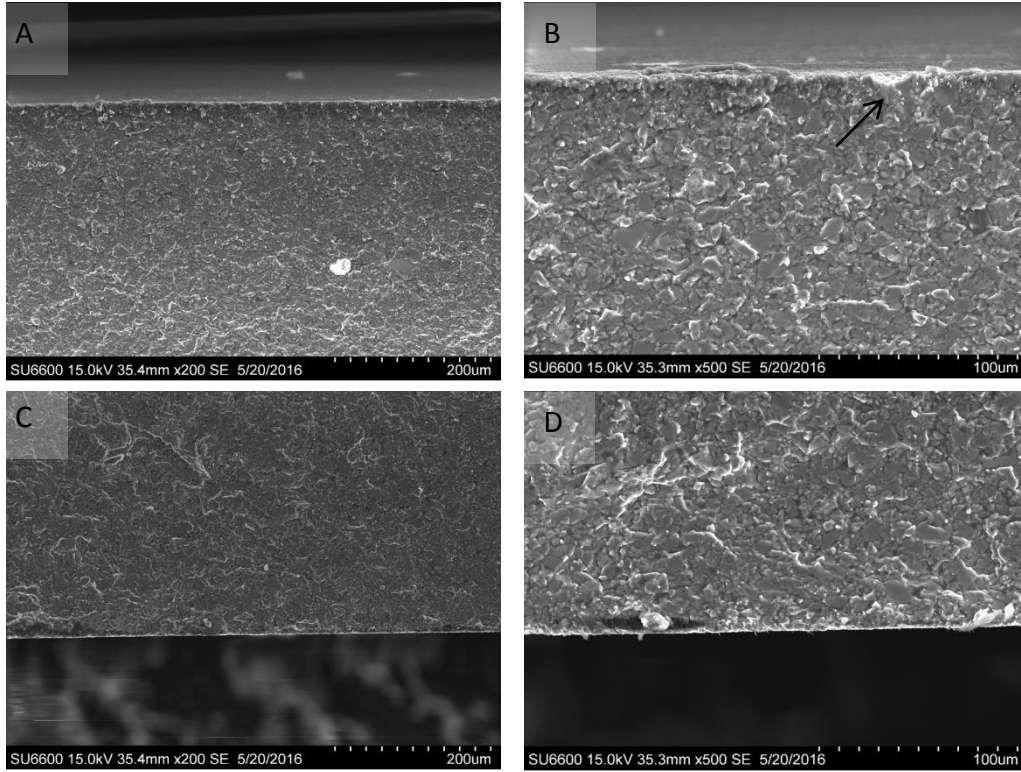


Figure 36: SEM image of fracture site for Vita Enamic saw cut group: A, B compression side of fracture site. C, D tension side. Arrow indicate possible chipping damage.

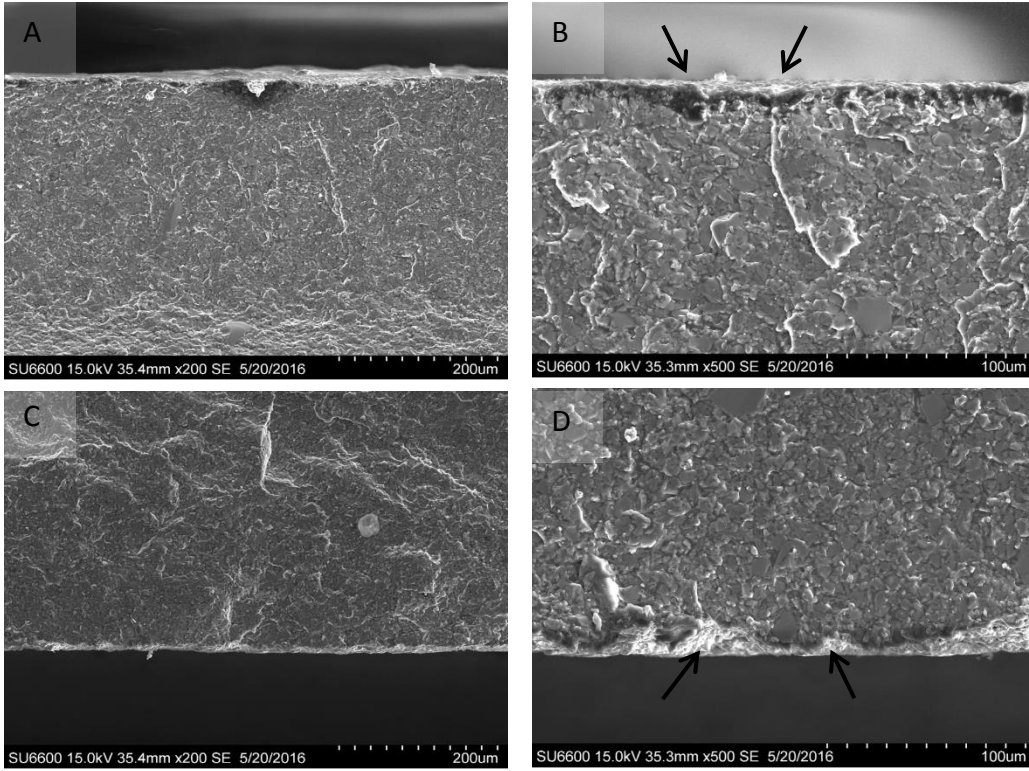


Figure 37: SEM image of fracture site for Vita Enamic normal mill group: A, B compression side of fracture site. C, D tension side. Arrow indicate possible chipping damage.

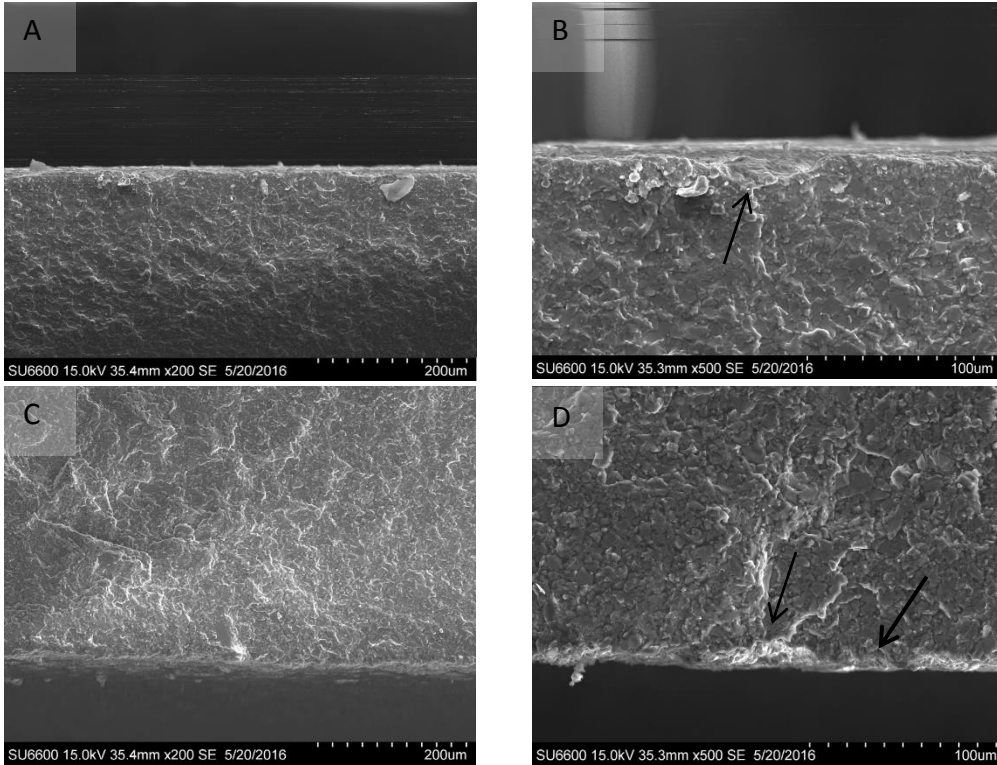


Figure 38: SEM image of fracture site for Vita Enamic fast mill group: A, B compression side of fracture site. C, D tension side. Arrows indicate possible chipping damage.

### 3.4 Vita Mark II

#### 3.4.1 Flexural strength

The flexural strength of the Vita MKII saw cut group was  $141 \pm 8.2$  MPa, for the normal mill group  $117.86 \pm 12.76$  MPa and for the fast mill group  $114.56 \pm 7$  MPa. The measured surface roughness for the saw cut group in the longitudinal and transverse planes were  $0.12 \pm 0.16$   $\mu\text{m}$  and  $0.134 \pm 0.14$   $\mu\text{m}$  respectively. The measurements for the normal mill

group  $1.45 \pm 0.24 \mu\text{m}$  in the longitudinal plane and  $1.18 \pm 0.16 \mu\text{m}$  in the transverse plane. The fast mill group surface roughness longitudinal measurement was  $1.41 \pm 0.29 \mu\text{m}$  and the transverse measurement  $1.3 \pm 0.18 \mu\text{m}$ . Looking at the statistical analysis, the flexural strength of the saw cut group had significantly higher flexural strength than both normal mill ( $P = 0.0088$ ) and fast mill group ( $P = 0.0055$ ). There was no significant difference between the flexural strength of the milled groups ( $P = 0.877$ ) (Figure 39) (Table 22). In terms of surface roughness, the saw cut group had significantly less roughness compared to both milled groups in the longitudinal and transverse planes ( $P < 0.0001$ ). There was no significant difference in the surface roughness between the normal mill and fast mill groups in both planes ( $P > 0.05$ ) (Figure 40, 41) (Table 24, 26).

The plot in Figure 42 shows the correlation between the flexural strength and Ra-L. The R-squared value for MKII is 0.64, means that there is a strong correlation between the surface roughness and flexural strength.

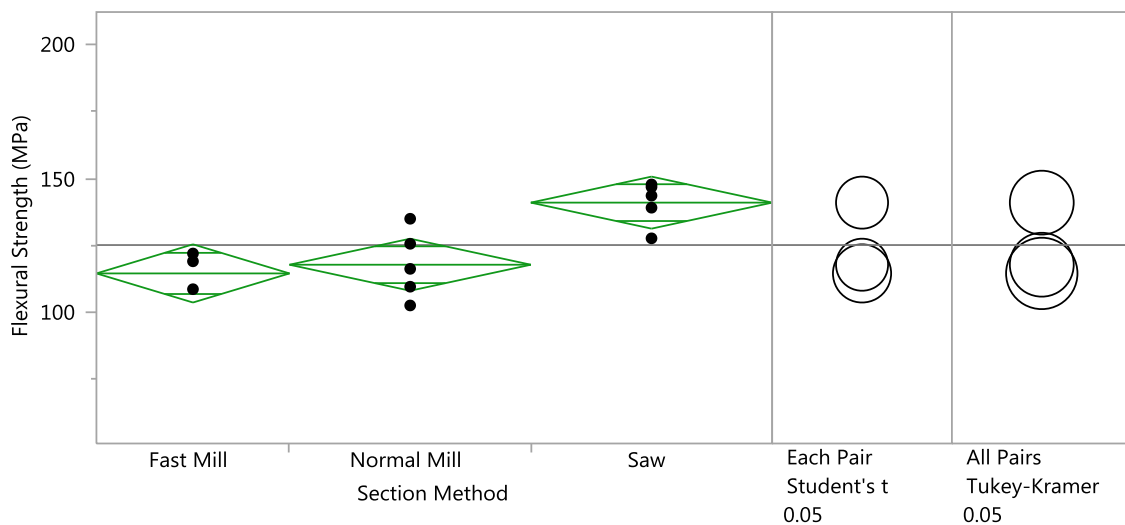



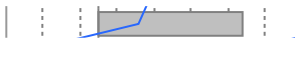

Figure 39: One-way analysis of flexural strength (MPa) by section method for Vita MKII

Table 21: Connecting Letters Report for flexural strength of Vita MKII

Level			Mean
Saw	A		141.00600
Normal Mill		B	117.81600
Fast Mill		B	114.56250

\*Levels not connected by same letter are significantly different

Table 22: Ordered Differences report for flexural strength of Vita MKII

Level	Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value	
Saw	Fast Mill	26.44350	6.625089	8.5504	44.33658	0.0055*	
Saw	Normal Mill	23.19000	6.246194	6.3202	40.05976	0.0088*	
Normal Mill	Fast Mill	3.25350	6.625089	-14.6396	21.14658	0.8770	

### 3.4.2 Surface roughness

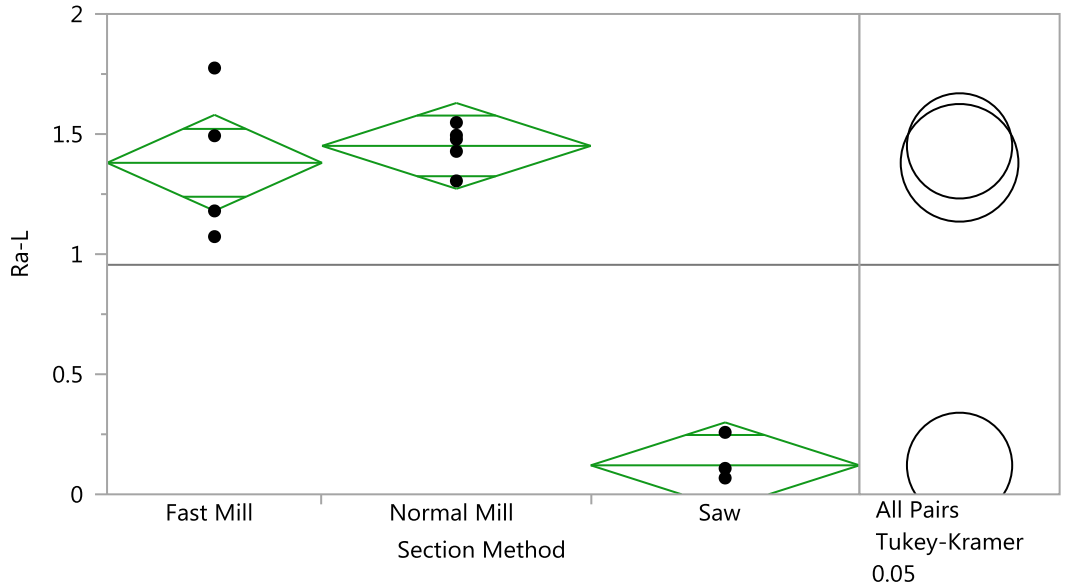


Figure 40: One-way analysis of Ra-L ( $\mu\text{m}$ ) by section method for Vita MKII

Table 23: Connecting Letters Report for Vita MKII CAD Ra-L

Level			Mean
Normal Mill	A		1.4508000
Fast Mill	A		1.3802500
Saw		B	0.1208000

\*Levels not connected by same letter are significantly different

Table 24: Ordered Differences report for Vita MKII Ra-L

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Normal Mill	Saw	1.330000	0.1147488	1.02009	1.639914	<.0001*
Fast Mill	Saw	1.259450	0.1217095	0.93074	1.588164	<.0001*
Normal Mill	Fast Mill	0.070550	0.1217095	-0.25816	0.399264	0.8336

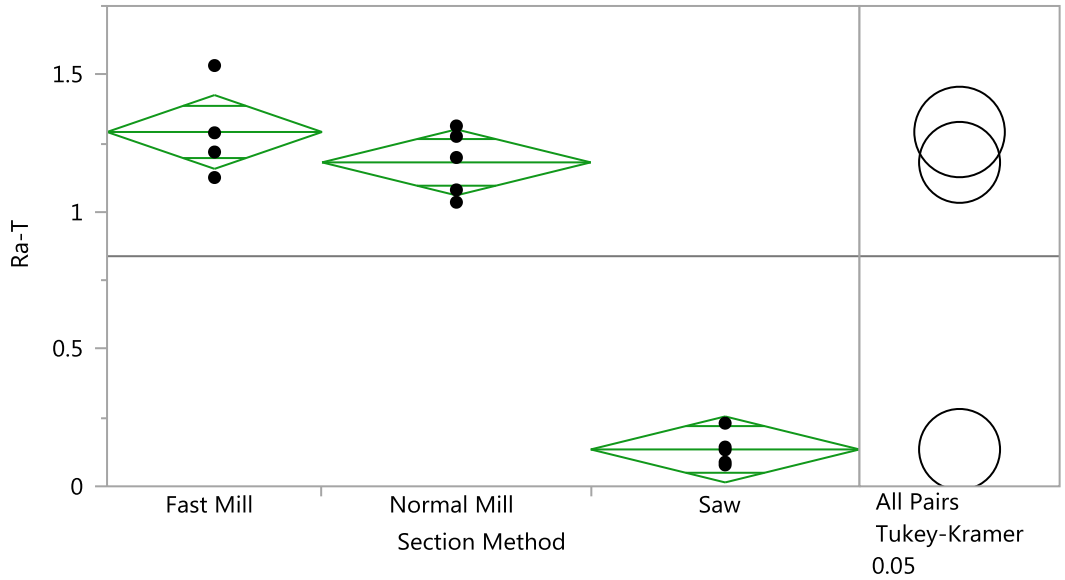


Figure 41: One-way analysis of Ra-T ( $\mu\text{m}$ ) by section method for Vita MKII

Table 25: Connecting Letters Report for Vita MKII CAD Ra-L

Level			Mean
Fast Mill	A		1.2910000
Normal Mill	A		1.1802000
Saw		B	0.1344000

\*Levels not connected by same letter are significantly different

Table 26: Ordered Differences report for Vita MKII Ra-T

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value	
Fast Mill	Saw	1.156600	0.0819265	0.935332	1.377868	<.0001*	
Normal Mill	Saw	1.045800	0.0772411	0.837187	1.254413	<.0001*	
Fast Mill	Normal Mill	0.110800	0.0819265	-0.110468	0.332068	0.3974	

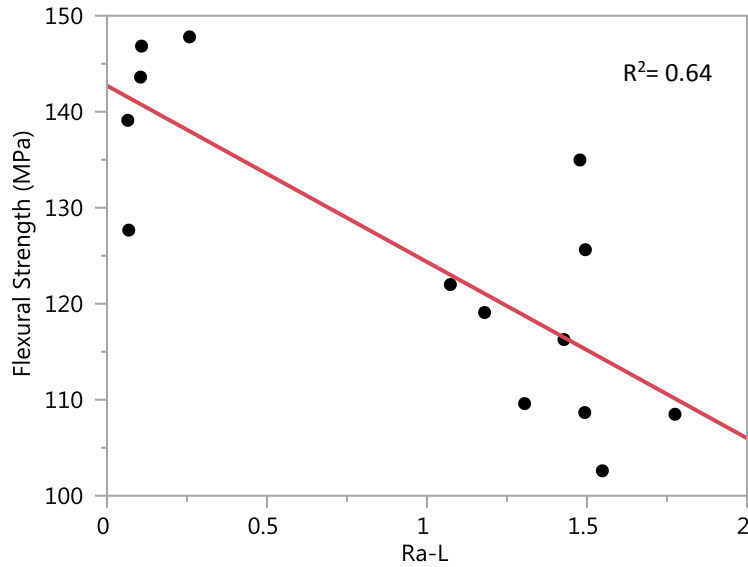


Figure 42: Bivariate Fit of Flexural Strength (MPa) By Ra-L for Vita MKII

### 3.4.3 Microstructural analysis

SEM images were taken on the fracture site (Figure 43-46). In Figure 43 it is observed, similar to e.max CAD and empess CAD, that the milled bars have rounded edges. The fracture started from the tension side. In Figure 44 the magnified segment in the saw cut bar shows that there is no significant edge damage. In contrast, the chip damage is obviously seen in Figures 45, 46 for the milled bars.

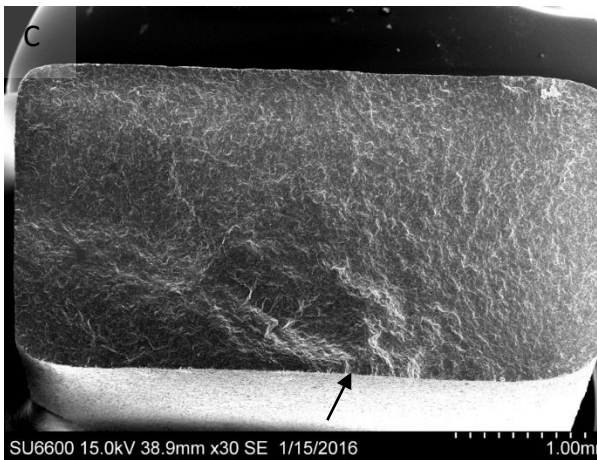
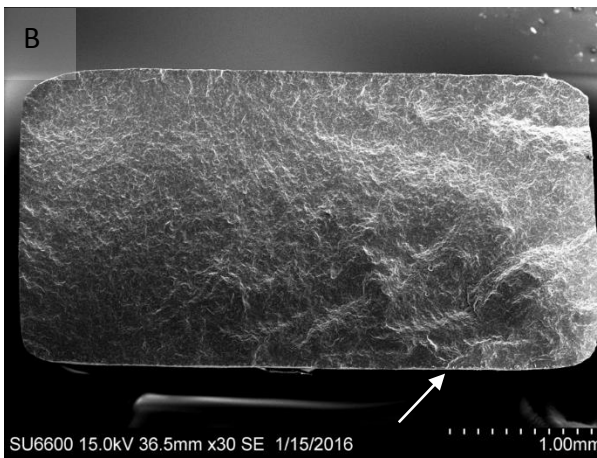
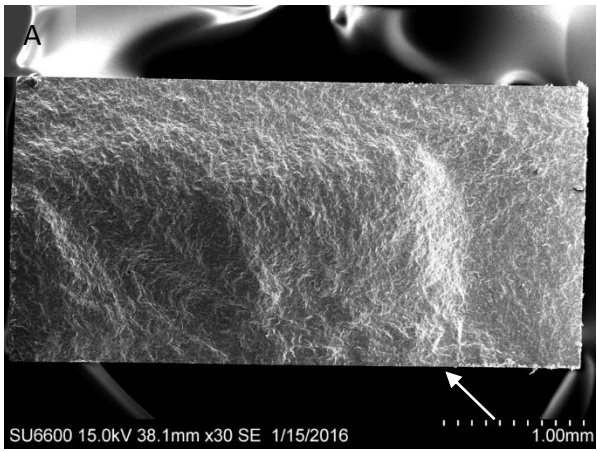


Figure 43: SEM image of fracture site for Vita MKII: A- Saw cut, B- Normal mill, C- Fast mill. The arrows indicate fracture starting point.

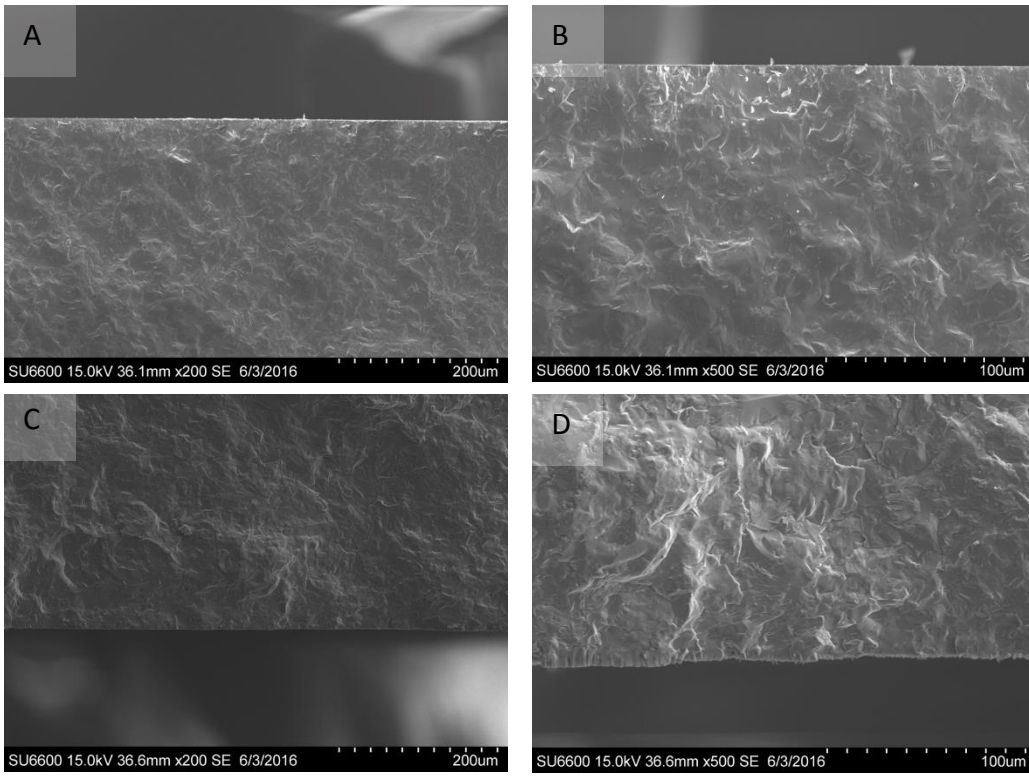


Figure 44: SEM image of fracture site for Vita MKII saw cut group: A, B compression side of fracture site. C, D tension side

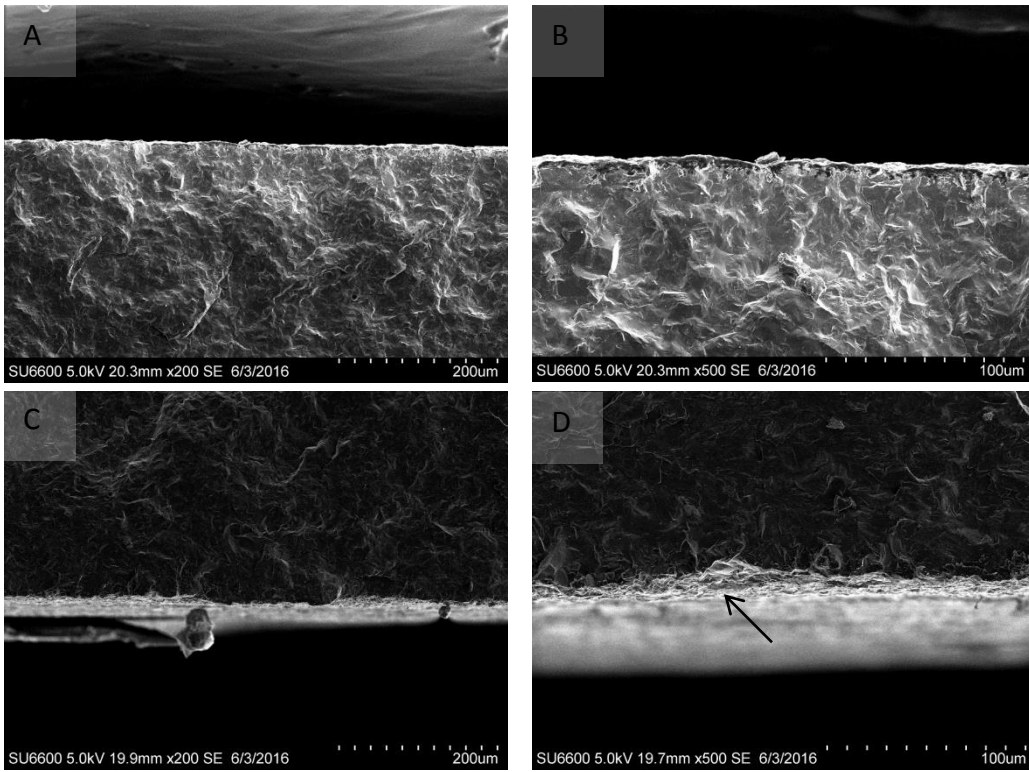


Figure 45: SEM image of fracture site for Vita MKII normal mill group: A, B compression side of fracture site. C, D tension side. Arrow indicate possible chipping damage.

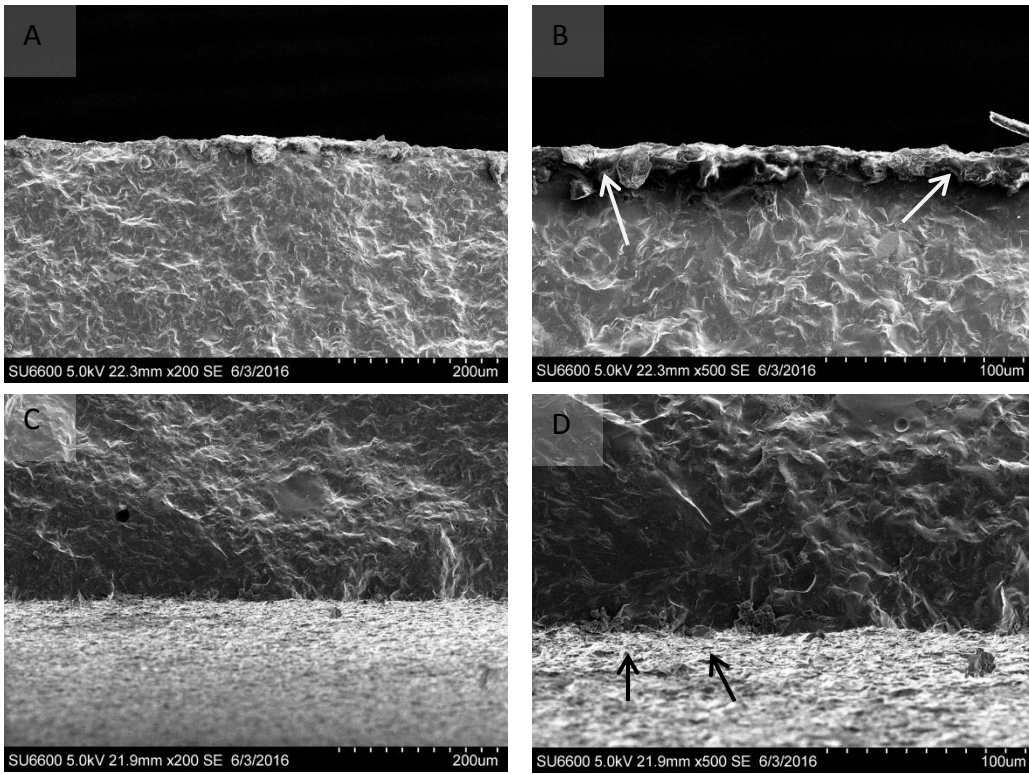


Figure 46: SEM image of fracture site for Vita MKII fast mill group: A, B compression side of fracture site. C, D tension side. Arrows indicate possible chipping damage.

## Chapter 4. Discussion

The null hypothesis that there is no difference in the surface roughness of between the saw cut and milled groups is rejected. As expected, the milling process causes more surface defects that is represented by higher surface roughness in the machined bars in all of the materials compared to their saw cut counterparts. However, the milling speed, normal and fast, produced similar surface roughness values.

Milled e.max bars exhibited lower flexural strength than the saw cut group. As such the null hypothesis is rejected. This does suggest a link between the surface roughness and the flexural strength. A study by Rushcel *et. al.*<sup>41</sup>, examined e.max pressed bars, did not find a difference in the flexural strength in the groups despite the difference in Ra values. In the current study, however, the difference in magnitude in the Ra values measured between the saw cut and milled groups was much higher. This suggests that there might be a range where the increase in surface defects can cause a significant drop in strength. This also supported by Lohbauer *et. al.*<sup>42</sup>, where they demonstrated a linear correlation between the surface roughness and flexural strength for e.max press.

However, the there was no significant difference observed in the tested groups for Empress CAD. The null hypothesis cannot be rejected. One possible explanation is the high leucite content (45% volume) which may have contributed to less machining damage. Another explanation is the low sample size used in this study from observing the LSN for the

EMPRESS CAD, which is 40.4, meaning that at least 40 bars are required to observe significant difference.

In the case of Enamic, the null hypothesis is partially rejected. The flexural strength for the saw cut group was significantly higher than the normal mill group. This result supports the association between surface roughness and flexural strength. However, there was no significant difference observed between the saw cut group and the fast mill one. Again, one possible explanation for the result is the small sample size since the LSN for Enamic was 11.6. Another possibility is that during the fast milling process plastic deformation may have occurred that reduced machining damage. As such, the correlation between the strength and the surface roughness, represented by R-squared = 0.28, is not as strong as e.max CAD and Vita MKII. Since Enamic is a newly introduced material, further research is needed to investigate its properties.

Finally, for Vita mark II, the null hypothesis is rejected. This further supports the association between the surface roughness and flexural strength. There was no significant difference between the milled groups. The R-squared value of 0.64 shows the strong correlation between the strength and the surface roughness. This is supported by a study by Giordano *et. al.*<sup>37</sup>, which showed that reducing surface defects through polishing, over glazing, and ion exchange can significantly improve the strength of ceramics.

As mentioned earlier, there was no significant difference in flexural strength between normal mill and fast mill of Empress CAD, Enamic and Vita MKII. This suggests that we

can fabricate crowns with the CEREC machine using the fast setting without a concern of decreased flexural strength. That being said, it is assumed that the faster setting of the CEREC machine increases the feed rate of the burs into the block to reduce the milling time. As such, one should be careful of potential chipping damage at the thinnest portions of the crowns, particularly around the margins.

Further research can be done with increasing the sample size to verify the effects of the machining damage on the Empress CAD and Enamic. Additionally, a continuation of this study is to mill the bars and examine the effects of polishing on their flexural strength. Furthermore, although chipping damage was observed in the study, it was not the main focus. An interesting topic would be to examine the edge chipping damage that can occur from the milling process and its effects on the mechanical properties of the ceramics. Moreover, more research is needed to study the different milling methods and surface chipping patterns as well as fracture patterns of the different materials to have a better understanding of CAD/CAM ceramics behavior.

## Conclusion

With the limitations of this study the following conclusions are drawn.

- Milled e.max CAD bars had significantly lower flexural strength than saw cut bars.
- There was no significant difference in flexural strength between the tested groups of Empress CAD.
- Enamic saw cut bars had significantly higher flexural strength compared to normal mill but not fast milled bars. There was no difference between milled groups.
- Vita MKII saw cut bars had significantly higher flexural strength compared to both milled groups. There was no difference between the milled groups.
- Surface roughness values of the materials in all saw cut groups were significantly lower compared to that in the milled ones.
- e.max. CAD and Vita MKII had strong correlation between Ra and flexural strength.
- Vita Enamic had weak correlation between flexural strength and surface roughness.

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Ministry of Health of The State of Kuwait, January '08- December '08  
Provided dental care in the various dental specialties: Prosthodontics, Periodontics, Oral surgery, Endodontics and Orthodontics
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- 10 week Rotational Externship**  
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Provide patients with primary and emergency dental care. This includes treatment planning, placement of direct restorations, extractions, pulpectomies and referral to the specialists.
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Main duties include: organizing the dental team's schedule, implementing new administrative policies, checking and restocking the dental inventory

**Teaching** April 09- 2012. Responsible for supervising new dental school graduates and help them transition from dental school to government practice setting.

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Massachusetts Dental Society 2003-Present  
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Boston, MA 5/8-5/13/2006

**Professional  
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FDI Dubai, 2007 International Dental Congress  
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References Available Upon Request