CUTTING EFFICIENCY OF DIAMOND BURS ON YTTRIA-STABILIZED ZIRCONIA AND LITHIUM DISILICATE INGOTS

A Thesis

by

ANDREINA CORDIDO ENRIQUEZ

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	William Nagy
Committee Members,	Jorge Gonzalez
	David Murchison
	Peter H. Buschang
Head of Department,	Larry Bellinger

May 2016

Major Subject: Oral Biology

ABSTRACT

The purpose of this *in vitro* study was to assess the cutting efficiency of diamond burs on Y-TZP Zirconia as measured by heat generation during cutting; time needed to cut 4 mm of an ingot shaped specimen; and material lost after cutting compared to a Lithium Disilicate control. Forty six cuts of each material were made in a custom test device that held the handpiece in a fixed position and moved the sample toward the cutting bur. Measurement of time, temperature change and weight loss were made to describe the cutting efficiency of a diamond bur.

The amount of time needed to cut Zirconia was almost three times longer than the time needed to cut Lithium Disilicate and was found statistically significant ($P < 0.001$) in an Independent Sample Test.

The temperature decreased during the cut, but this change was not significant, suggesting that using water coolant would control temperature change.

A Pearson Correlation test demonstrated the duration of the cut was related to both temperature and change of temperature for Zirconia but not for Lithium Disilicate, suggesting that the longer the cut for Zirconia the lower the temperature and the larger the change in temperature.

There was a significant difference ($P < 0.001$) for material loss for each group and also in the comparison of material loss between the two groups, Zirconia losing double of the weight than Lithium lost. This should be described as a proportional loss,

as Zirconia is heavier than Lithium Disilicate, therefore the weight of material loss for Zirconia is greater than for Lithium Disilicate

Within the limitations of this study it can be concluded that the amount of time needed to cut Zirconia was almost three times longer than the time needed to cut Lithium Disilicate. There was no significant heat generation when water spray was used. The material loss for Zirconia was double that for Lithium Disilicate.

DEDICATION

This work is dedicated to my husband, Mandy. You are the one that has made possible this project of life. I thank you for your unconditional support, patience and for each encouraging word you have told me in each step of this process. I could not have done it without you. I love you with all my heart.

To my parents, Alberto and Alejandra. You have always been by my side in each decision I make, and sharing with me every day every detail of my growing process that has brought me to where I stand today. Thank you for been my guide.

To my siblings, Amalia y Andres. I am proud of both of you and the person you have become. Thank you for your support and friendship.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. William Nagy, and my committee members, Dr. Jorge Gonzalez, Dr. David Murchison, Dr. Peter Buschang, PhD, for their guidance and support throughout the course of this research.

To my director and mentor, Dr. William Nagy, there are no words to thank you enough for your dedication to teach. You make a difference in the life of every resident, and are the best example of knowledge and integrity one can have. Thank you.

To my husband Mandy Barsilai and our friends David Guidry and Bhavna Kumar, for your hard work and support to design and build the device used in this study and to spend a good amount of time away from your family to help me finish this project.

Special thanks to Dr. Goodman, your kindness and knowledge of life have make me become a better person, thank you.

Thanks to John Woody at Brasseler for providing the burs and handpiece used in the study and to Rynhard Venter at Archworks for your willingness to fabricate the Zirconia specimens.

Thanks also go to my friends and colleagues, the department faculty and staff for making the Graduate Prosthodontics Program a great experience.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION AND LITERATURE REVIEW

With the increasing demand for highly esthetic restorations, specialized ceramics have been introduced as an option for dental restorations. Ceramic materials can successfully replicate the esthetic qualities of natural teeth and have low thermal conductivity, however, despite their strength under compression, they are brittle materials, with limited tensile strength, and do not exhibit plastic deformation before failure [2]. All of these characteristics are very important when deciding the material to be used to restore a patient, as they will be determinants of whether ceramics will be the right choice.

In the search for the ideal dental ceramic, there has been a growing interest in yttria stabilized Zirconia (Y-TZP) that can be used as a replacement for metal alloy substructures and for full contour restorations. Yttria stabilized Zirconia (Y-TZP) has excellent mechanical properties such as high fracture toughness and biocompatibility [3], two of the most important characteristic for a restorative material in dentistry.

When compared with other ceramics, Y-TZP Zirconia has outstanding strength and toughness. The toughness is due to a tetragonal to monoclinic transformation, whereby the metastable tetragonal phase transforms under stress into the thermodynamically more favorable monoclinic phase. This transformation is associated with a 3-4% volume expansion, which reduces the stress intensity at the top of an advancing crack [3, 4].

Zirconia has been widely used as a biomaterial since 1970, but it was not introduced to restorative dentistry until around 2004. After more than 25 years of use in the medical field, some failures were reported; in 2001-2002, several hundred Y-TZP femoral heads failed in a short period of time, with the origin of the fracture clearly associated with the hydrothermal degradation of the material [11]. However, for dental Zirconia no such failure have been reported.

Interestingly, hydrothermal degradation is not well understood for dental Y-TZP Zirconia. In contrast to the orthopedic community, some dental researchers do not seem to be concerned by ageing problems, presumably anticipating that veneering and luting materials, separating the core from the oral environment and hard dental tissues, provide for a durable protection of dental Zirconia against hydrothermal decomposition [11]. Even when this last idea sounds logical, is it controversial and the subject of several studies trying to define the actual degree of hydrothermal degradation of the Y-TZP Zirconia. Furthermore, recent investigation has shown that commonly used luting cements absorb water via dentine tubules, thereby exposing the Zirconia core to moisture, which, in turn, may lead to ageing problems over a shorter period of time than anticipated [12]. Interestingly, hydrothermal degradation is not well understood for dental Y-TZP Zirconia.

In the interest of clarifying characteristics of dental Y-TZP Zirconia, some studies had focused on veneered Zirconia framework FDP’s, with data up to 5 years, a high prevalence of chipping of the ceramic veneering material has been reported. This chipping seems to be more frequent for all-ceramic restorations than for porcelain fused to metal restorations. Fracture of Zirconia frameworks have been rarely reported [5].

However, there are three disadvantages of an all-Zirconia crown: the difficulty in adjusting occlusion when significant premature contacts are present, the cutting difficulty, and the potential heat generated when removing defective crowns or when making an endodontic access opening with diamond burs [1].These are important considerations to have in mind when planning for a Y-TZP Zirconia restoration, and the patient should be aware of these disadvantages.

While surface grinding may increase surface toughening in principle through the tetragonal to monoclinic phase transformation (referred as t–m transformation), excessive grinding of the material is not recommended by most manufacturers. Surface grinding may introduce residual compressive stresses that can increase the strength of Zirconia-toughened ceramics considerably while on the other hand, severe grinding may introduce deep surface flaws, which act as stress concentrators [6].

Zirconia also suffers a spontaneous t–m phase transformation at the surface when it is exposed to humid environments. This phenomenon, referred to as hydrothermal degradation or low temperature degradation, results in the loss of mechanical properties because of the formation of intergranular microcracks in the surface degraded layer.

On the other hand, during final shaping and surface finishing the ceramic is exposed to different types of machining processes (cutting, grinding, polishing, diamond drilling, sandblasting, CAD/CAM machining, etc.). All these processes induce different types of damage as phase transformation, plastic deformation or cracks that may also affect the structural integrity of Y-TZP Zirconia [13].

Although studies are trying to define all of Y-TZP Zirconia's characteristics, ceramic restorations have been used long enough to begin exhibiting clinical failure requiring restoration removal. A Clinician Report's survey showed that 98% of clinicians have had to remove Zirconia and Lithium Disilicate restorations [15].

Removal of crowns has long been a major concern and perplexing problem for dentists. There are several reasons why a dentist may have to remove a crown, including, a crown that is incompletely seated at the time of cementation; marginal leakage and dissolution of cement; endodontic treatment is needed; or there is some chipping or flaking of the porcelain [14].

Tooth-colored Zirconia and Lithium Disilicate ceramics can be challenging to remove because the material is hard and difficult to cut, esthetic ceramics can be difficult to distinguish from the underlying cement and tooth, and when well bonded, restorative materials may not easily release from underlying tooth structure [15].

The primary concern of a dentist when attempting to remove a crown, should be to prevent damage of tooth structure and pulpal or periodontal tissues and to minimize trauma to the patient. The crown can be remade anytime, as long as there is enough tooth structure and any further treatment needed for the success of the restoration is addressed.

When removing PFM or full-metal crowns, dentists have been accustomed to the simple task of making a slot in the restoration with a bur, placing a screwdriver-like instrument in the slot, and popping the crown off with little or no difficulty. Such is not the case with all-ceramic restorations. The arduous task of making slots in the restoration and slowly chipping the material from the tooth, piece by piece, is well known to dentists.

Efficiency is the parameter that refers to the extent to which time, effort, or cost is well-used for the intended purpose. Machinability is defined as the relative ease of machining a material [7]. The operational characteristics of a cutting tool are generally described by this single word [9]. There are usually three criteria used for discussing machinability: tool life, surface finish, and power required to cut [8].

Therefore, cutting efficiency can be measured as the time required to cut a certain distance, heat generated, the quality of the cut, and the amount of material lost during the cutting process.

To our knowledge, there have been no reports on the cutting efficiency and heat generated in removing defective yttria-stabilized Zirconia crowns. The purpose of this in-vitro study is to assess the cutting efficiency of diamond burs on Y-TZP Zirconia as measured by heat generation during cutting; time needed to cut 4 mm of an ingot shaped specimen; and material lost after cutting compared to a Lithium Disilicate control. The null hypotheses were: 1.There would be no difference in the time needed to cut 4mm of yttria-stabilized Zirconia with a diamond bur, than the time needed to cut 4mm of Lithium Disilicate. 2. There would be no difference in the heat generated while cutting 4mm of yttria-stabilized Zirconia with a diamond bur, than that while cutting 4mm of Lithium Disilicate. 3. There will be no difference in the weight loss of yttria-stabilized Zirconia and Lithium Disilicate after cut with a diamond bur.

2. MATERIAL AND METHODS

2.1 Test Device

The test device was designed to perform the cutting tests in a standardized manner, and the design is shown in Figure 1.

Aluminum metal pieces were cut and assembled in a base of 25 x 10 inches with a vertical wall in the middle to support the electric motor hand piece and specimen holder. The holder was supported by two linear bearings placed on parallel rods and was designed to move toward the hand piece with a controlled force.

An electric motor handpiece (Forza ELM from Brasseler USA) was mounted and secured to the vertical wall of the cutting machine. The attachment was adjustable to be able to set the handpiece perpendicular to the sample and produce a 2 mm engagement height. The horizontal position of the instrument could be set to produce a central cut on the cylindrical sample block.

The amount of force used to move the sample was also controlled using a principle using on previous studies [10], a pulley system attached to the holder on one side and on the other side a calibrated weight (Aqua Culture Aquarium Gravel).

The specimen holder was in contact with a position sensor (TT Electronics/BI Manufacturer) used to measure the distance of the cut.

2.2 Software Design

A customized software program (constructed using Visual basic from Microsoft) was designed to record the position and time of the specimen at intervals of 0.02 seconds. The position was calibrated for each cut and a time stamp was recorded at each position to generate as many data points as possible to calculate position related to time.

The program would record the starting point as point “0” and position and time were graphed in “real time” during the cut (Figure 2). After the distance exceeded 4 mm the recording was stopped.

2.3 Electric Handpiece

The electric motor handpiece (Forza ELM, Brasseler USA) was operated at 40,000 rpm with a 120ml/min coolant water spray. Two handpiece attachments were used, both were Brasseler USA Forza 5 Attachment (Gear ratio 1:5 Increasing) allowing a maximum rotation speed of the cutting bur of 200,000 rpm. Each attachment had four port water sprays.

2.4 Specimen Fabrication

Twelve cylindrical specimens were used in the experiment and divided into 2 groups (Figure 3). The shape of all the samples resembled the IPS e.max Xpress Ingots (cylinder area of 673.87 mm^2, volume of 1327.32 mm^3, with a radius of 6.5 mm and height of 10 mm). 8 cuts were made in each ingot (4 cuts in each horizontal face). (Figure 4).

Group 1: Six (6) IPS e.max Xpress Ingots, shade A2 in their commercially available shape.

Group 2: Six (6) Zirconia specimens were cut from the commercially available 18mm Zirconia blocks, forming a cylinder with a radius of 6.5 mm and height of 10 mm. (Zirconzahn Prettau Zirconia Italy milled by Archworks Lab, Waco, TX.)

There were a total of 46 cuts per group.

2.5 Measurement of Material Loss

In order to report the amount of substrate lost during cutting, each of the 12 samples were weighed before and after each cut (Vi-200 scale, ACCULAB), the scale was calibrated before each cut, accuracy of the scale was 0.01 gr.

2.6 Measurement of Temperature Change

The temperature rise (°F) during the cut was measured from a distance of approximately 20 inches using an infrared thermometer (Ryobi Tek4 Professional 4-Volt Infrared Thermometer). The measurement point was the contact between the bur and the sample (Figure 5). The initial temperature recorded was made when the bur touched the sample while the handpiece was turned off, and no coolant was being sprayed. Once the bur starting cutting, the temperature was recorded approximately every 30 seconds during the cut, until the 4 mm distance was accomplished.

2.7 Cutting Procedure

The test specimen was mounted in the custom aluminum specimen holder which moved perpendicularly toward the handpiece and cutting bur. The bur was set to cut 2mm vertically into the sample. Weight was added to the bag on the side of the pulley assembly until the resistance from the assembly was surpassed and then ballast was removed as needed for calibration. Then an additional 142 grams was added to apply a constant force of 5 oz.

The sample weight was recorded before placing the sample in the holder. After the sample was secured in the holder it was moved by the weight until it touched the bur. This position was recorded as position 0 and the initial temperature was recorded.

The holder was retracted to turn on the handpiece, and once the handpiece and the coolant were functioning, the sample was self-propelled by the pulley system. The handpiece was maintained at the same rpm until the distance cut was 4mm. The temperature was measured and recorded approximately every 30 seconds. After the 4 mm distance was cut, the handpiece was stopped and the sample was removed from the holder, dried and weighed.

This procedure was repeated for every cut. Each cut was made with a brand new Brasseler FG coarse duracut RE taper (#6856 DC.31.018) bur. This diamond bur is made of stainless steel and coated with diamond particles utilizing a patented bonding process that the manufacturer assures improves the cutting efficiency of the bur.

2.8 Statistical Analysis

An a priori power analysis was run before the experiment and it was determined that 46 cuts of each material were required to demonstrate a strong correlation (α=0.5) and to have 95% power (1-β err prob = 0.95).

An independent t test was used to evaluate the differences between time and temperature change during each cut for Zirconia and Lithium Disilicate. Correlation between time and temperature was determine for both groups.

The data was organized as Time 0 seconds (initial time), 30 seconds and the final time for each cut, and the statistical analysis was based on the differences between the initial time and measurements at 30 seconds, and between initial time and final time.

A one Sample-t test was used to evaluate the differences in material loss for Zirconia and Lithium Disilicate

3. RESULTS

3.1 Cutting Time

The amount of time needed to cut Zirconia was longer than the time needed to cut Lithium Disilicate. Zirconia times ranged from 30.00 seconds to 450.00 seconds with a mean of 150.00 seconds and a median of 143.249 seconds to cut 4 mm at 2 mm of depth. (Tables 1 and 2). Lithium Disilicate times ranged from 30.00 seconds to 90.00 seconds with a mean of 38.48 seconds and a median of 55.81 seconds. (Tables 1 and 2). There was a statistically significant difference ($P < 0.001$) on the duration of the cut when taken from 30 seconds to the end of the cut Zirconia's mean was: 120 seconds and Lithium Disilicate was 8.47 seconds. (Table 3 and 4).

3.2 Temperature Related to Time

A Pearson Correlation test demonstrated a correlation between duration of the cut and both the temperature and the temperature change during the cut for Zirconia, suggesting that the longer the cut the cooler the sample will get. This is not the same case for Lithium Disilicate, where the temperature change was independent from the time. (Tables 5 and 6).

3.3 Temperature Change

The mean sample temperature during the cut for Zirconia was 71.6 ^{0}F and 72.2^{0}F for Lithium Disilicate. (Table 1).

The temperature decreased during the cut, with a variation of .0174 degrees for Zirconia and 0.0065 degrees for Lithium Disilicate. (Table 2 and 3). No statistically significant difference was found for temperature change between the two groups. (Table 4).

For both groups the temperature change from time 0 (handpiece turned off) to time 30 (30 seconds) shared a statistically significant decrease ($P < 0.001$), but no significant change was observed during the cut. (Table 4).

3.4 Material Loss

The material loss for Zirconia ranged from 0.03 gr to 0.10 gr with a mean of 0.06 gr (Table 7 and 8) and for Lithium Disilicate from 0.01 to 0.07 gr with a mean of 0.03 gr (Table 10 and 11). There was a statistically significant difference ($P < 0.001$) for each group (Tables 9 and 12) and also in the comparison of material loss between the two groups, Zirconia losing twice the material weight that Lithium Disilicate lost. (Tables 13 and 14).

4. DISCUSSION

The amount of time needed to cut Zirconia was almost three times longer than the time needed to cut Lithium Disilicate (average of 150.00 and 38.48 seconds respectively) and statistically significant ($P < 0.001$). Therefore, the first null hypothesis that stated: there would be no difference in the time needed to cut 4 mm of yttria-stabilized Zirconia with a diamond bur, was rejected. This finding agrees with the results from a previous study that compared the cutting efficiency of diamond burs, using an electric high-speed dental handpiece, on Zirconia (Zir) with those on Lithium Disilicate glass–ceramic (LD) and leucite glass–ceramic (L). Tests were performed using diamond burs with super coarse (SC) and coarse (C) grain size. They reported that Zirconia with a thickness of 1.0 mm took a significantly longer time to be cut than other ceramics of the same thickness [17].

The length of time for cut showed an unexpected wide range of variance; for Zirconia the time ranged from 30.00 seconds to 450.00 seconds with a median of 143.249 seconds; and for Lithium Disilicate the time ranged from 30.00 seconds to 90.00 seconds with a median of 55.81 seconds (Figures 6 and 7). This finding suggest that there might be differences in the diamond coating. Further studies would be beneficial to determine if there is a difference in the diamond grit or bonding on the surface of the burs from the same type, indicating a possible quality control issue. An SEM evaluation would be valuable.

Another consideration would be that the bur gets dull the longer it stays in contact with the material, which might explain why cutting a stronger material takes longer time.

When cutting intraorally, one important concern is heat generation during the cutting process. The heat is generated because of the friction between two surfaces at high speed. Interestingly, Zirconia exhibits unique mechanical and electrical properties, like heat insulation [1].

In this study, temperature was measured at the initial time with the handpiece turned off, and no coolant was being sprayed, and then approximately every 30 seconds during the cut, until the 4 mm distance was accomplished. The temperature decreased during the cut, with a variation of .0174 for Zirconia and 0.0065 for Lithium Disilicate. Both groups' temperature decreased the same amount (1 to 2 degrees), which can be attributed to the characteristics of the water coolant spray. Therefore, the second null hypotheses that stated: there would be no difference in the heat generated while cutting 4 mm of yttria-stabilized Zirconia with a diamond bur, than that while cutting 4 mm of Lithium Disilicate, is not rejected.

The temperature and the temperature change were related to the duration of the cut for Zirconia but not for Lithium Disilicate. This suggests that the longer the cut for Zirconia the lower the temperature and the larger the change in temperature during the cut. This may account for the average temperature for Zirconia (71.65 ^{0}F) being less than Lithium Disilicate (72.20^{0}F).

The material loss for Zirconia (0.06 gr) was double than for Lithium Disilicate (0.03 gr). Zirconia is heavier than Lithium Disilicate, therefore the weight of material loss for Zirconia is greater than for Lithium Disilicate. Thus the third null hypotheses which stated: there will be no difference in the weight loss of yttria-stabilized Zirconia and Lithium Disilicate after cut with a diamond bur, is rejected.

The loss of material might be also seen as a proportional loss, were in average the loss for Zirconia and Lithium disilicate was around 1%, which means that the amount of material loss for both might be proportionally the same.

The design of the study allowed for controlling variables that would have influenced the results, leading to obtain clean results for time, temperature and material loss from the cutting test.

A study tested Lithium Disilicate ingots to assess the biaxial flexural strength, Vickers hardness, and fracture toughness of three pressing processes. Compared to the unpressed group, they found no significant difference in the biaxial flexural strength of the groups [16]. The hardness of the material decreased, and no significant difference was seen in fracture toughness with repeated pressings. This concept was key in the decision of using the Lithium Disilicate ingot in its commercially available form.

The use of the same type of bur for all the cuts controls for variance of grain size, also the surface contact of the bur with the specimen was standardized using only one bur shape. The use of a new bur for each cut allowed a fair comparison among the cuts. The calibrated weight allowed the cutting force to be the same for all the cuts. The cylindrical shaped sample size controlled for all cuts to be made orthogonal to the surface. The electric handpiece permitted the control for constant rpm and coolant spray. The positioning device for the handpiece and the sample holder of the machine were helpful on controlling the height of the cut to 2 mm vertical depth for all the specimens. The measurement of position related to time was made using a microcontroller to assure accurate recording of the cuts.

Funkenbusch described the cutting efficiency in terms of the rate of rotary instruments. They measured the effect of nine variables on the efficiency of a simulated dental cutting operation, the effects of 5 variables were judged as statistically significant. In order of importance, these were target applied load, cut length, starting rpm, diamond grit size, and cut type [18]. They did not take in account time and temperature which are also very important factors to describe cutting efficiency.

One of the limitations of this study is that the samples did not undergo thermocycling. The humidity of the oral environment has the potential to weaken ceramic dental restorations as a result of stress corrosion [2]. Some studies have investigated the time-dependent aging changes on Zirconia ceramics and found that Zirconia did not experience substantial change in flexural strength, even after 30 months of low temperature degradation [2, 14, 15]. Further studies should include thermocycling of the specimens to evaluate its effect on the cutting efficiency.

Grinding may introduce residual surface compressive stress that can increase the strength of Zirconia-toughened ceramics considerably while on the other hand, severe grinding may produce deep surface flaws, which act as stress concentrators and become strength determining if their length largely exceeds the depth of the grinding induced surface compressive layer [6]. This consideration is relevant when adjusting a fixed prosthesis to prevent internal flaws that can cause the failure of the restoration. In the case of removal of a failing restoration, creating internal flaws in the material will not be a problem.

In clinical practice, the use of water spray is key on maintaining a low temperature of the material during the cut, preventing heat generation that could affect vital teeth or implants when removing a fixed prosthesis. The dental practitioner should know that removing a Zirconia restoration seems to take three times longer than a Lithium Disilicate restoration, which means an increase in chair time.

Future studies should focus on cutting efficiency of different bur brands and configurations, to corroborate the finding of differences among the same type of burs that affected the cutting efficiency in this study. Another topic of interest can evaluate the difference of various amounts of force applied to cut, and report how this affects the temperature change and the length of the cut.

5. CONCLUSIONS

Within the limitation of this in vitro study, the following conclusions can be drawn:

1. The amount of time needed to cut Zirconia was almost three times longer than the time needed to cut Lithium Disilicate
2. Heat generation during cutting was well controlled by water spray.
3. The material loss (measured by weight) for Zirconia was double that for Lithium Disilicate, but was a proportional loss, (the loss for Zirconia and Lithium disilicate was around 1%).

REFERENCES

[1] Anusavice, K., Shen, C., & Rawls, H. *Phillips' Science of Dental Materials.* 12th edition. Elsevier Science, 2013.

[2] Papanagiotou, H., Morgano, S. *In vitro evaluation of low-temperature aging effects and finishing procedures on flexural strength and structural stability of Y-TZP dental ceramics*. J Prosthet Dent, 2006. **96**(3): p. 154-64.

[3] De Kler, M., De Jager, M. *Influence of thermal expansion mismatch and fatigue loading on phase changes in porcelain veneered Y-TZP Zirconia discs*. J Oral Rehabil, 2007. **34**: p. 841-847.

[4] Piconi, C., Maccauro, G. *Zirconia as a ceramic biomaterial*. Biomaterials, 1999. **20**(1): p. 1-25.

[5] Heintze, S., Rousson, V. *Survival of Zirconia- and Metal- Supported Fixed Dental Prostheses: A Systematic Review*. Int J Prosthodont, 2010. **23**(6): p. 493-502.

[6] Luthard, R., Holzuter, M. *CAD/CAM-machining effects on Y-TZP Zirconia*. Dent Mater, 2004. **20**(7): p. 655-662.

[7] Ohkubo, C., Watanabe, JP. *The machinability of cast titanium and Ti-6Al-4V*. Biomaterials, 2000. **21**(4): p. 421-428.

[8] Shaw, MC. *Metal cutting principles*. Oxford Clarendon Press, 1984.

[9] Di Cristofaro, R., Giner, L. *Comparative Study of the cutting efficiency and working life of carbide burs*. J Prosthodont, 2013. **22**(5): p. 391-396.

[10] Zettlemoyer, T., Goerig, A., Nagy, W. *Effects of sterilization procedures on the cutting efficiency of Stainless Steel and carbon steel gates*. J Endod, 1989. **15**(11): p. 522-5.

[11] Kosmac, T., Oblak, C. *The effects of dental grinding and sandblasting on ageing and fatigue behavior of dental Zirconia (Y-TZP) ceramics*. J Eur Ceram Soc, 2008. **28**: p. 1085-1090.

[12] Jevnikar, P. Sersa, I. *Effect on surface coating on water migration into resin-modified glass ionomer cements, a magnetic resonance micro-imaging study*. Magn Reson Med, 2000. **44**: p. 686-691.

[13] Munoz-Tabares, J.A., Anglada, M. *Hydrothermal degradation of ground 3Y-TZP*. J Eur Ceram Soc, 2012. **32**: p. 325-333.

[14] Piconi C, Burguer W, Richter H, Cittadini A, Maccauro G, Covacci V, et al. *Y-TZP ceramics for artificial joint replacement*. Biomaterials, 1998. **19**: p. 1489-94.

[15] Shimizu K, Oka M, Kumar P, Kotoura Y, Yamamuro T, Makinouchi K, et al. *Time dependent changes in the mechanical properties od Zirconia ceramic*. J Biomed Mater Res, 1993. **27**: p. 729-34.

[16] Gorman C, Horgan K, Dollard R, Stanton K. *Effects of repeated processing on the strength and microstructure of a heat-pressed dental ceramic*. J Prosthet Dent, 2014. **112**(6): p. 1370-1376

[17] Nakamura K, Katsuda Y, Ankyu S, Harada A, Tenkumo T, Kanno T, Niwano Y, Egusa H, Milleding P, O€rtengren U. *Cutting efficiency of diamond burs operated*

with electric high-speed dental handpiece on Zirconia..Eur J Oral Sci, 2015. **123**: p. 375–380.

[18] Funkenbusch P, Rotella M, Ercoli C. *Designed experiment evaluation of key variable affecting the cutting performance of rotary instruments.* J Prosthet Dent, 2015. **113**(4): p. 336-342

APPENDIX A

FIGURES

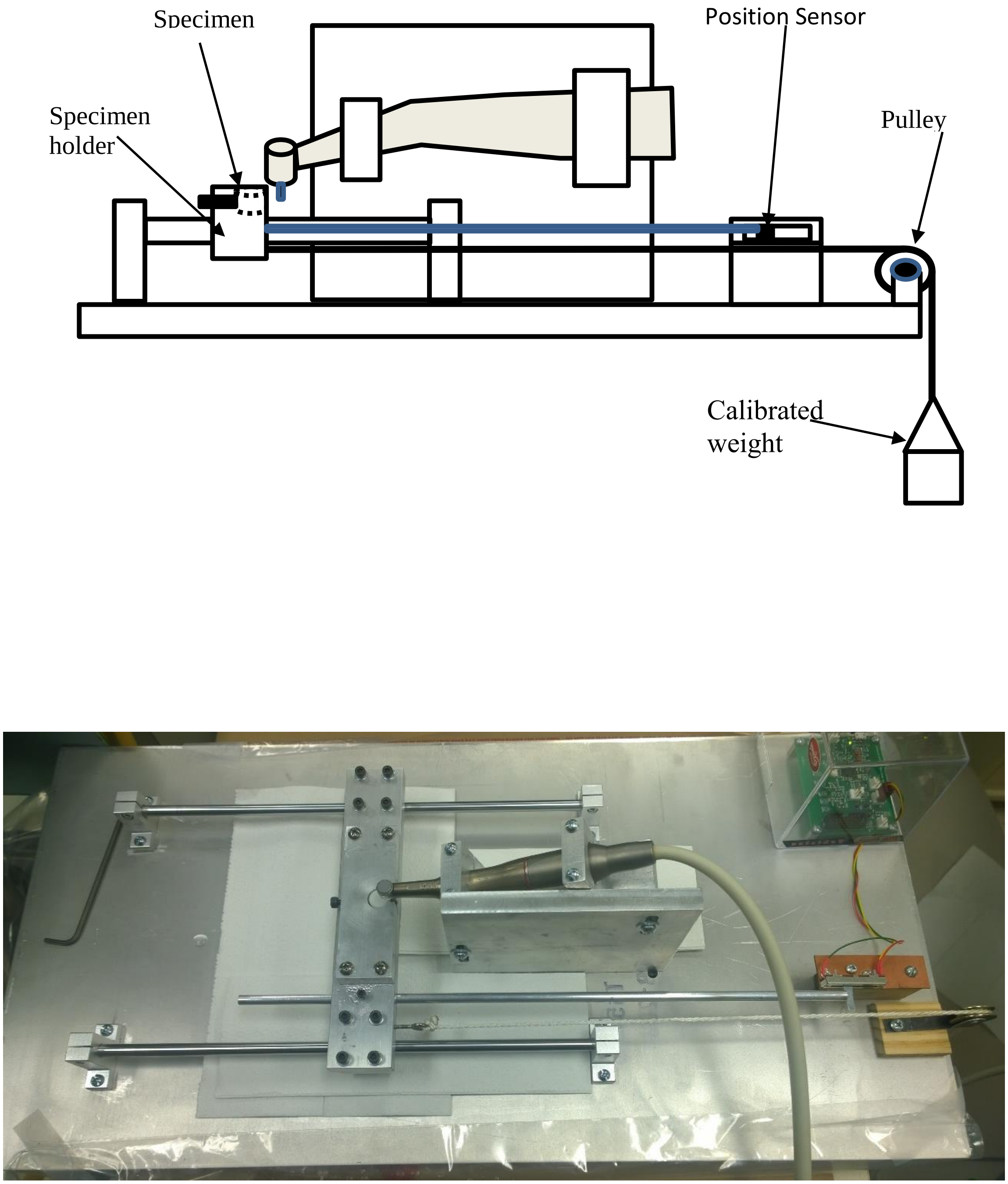


Figure 1: Schematic and photo of the test device

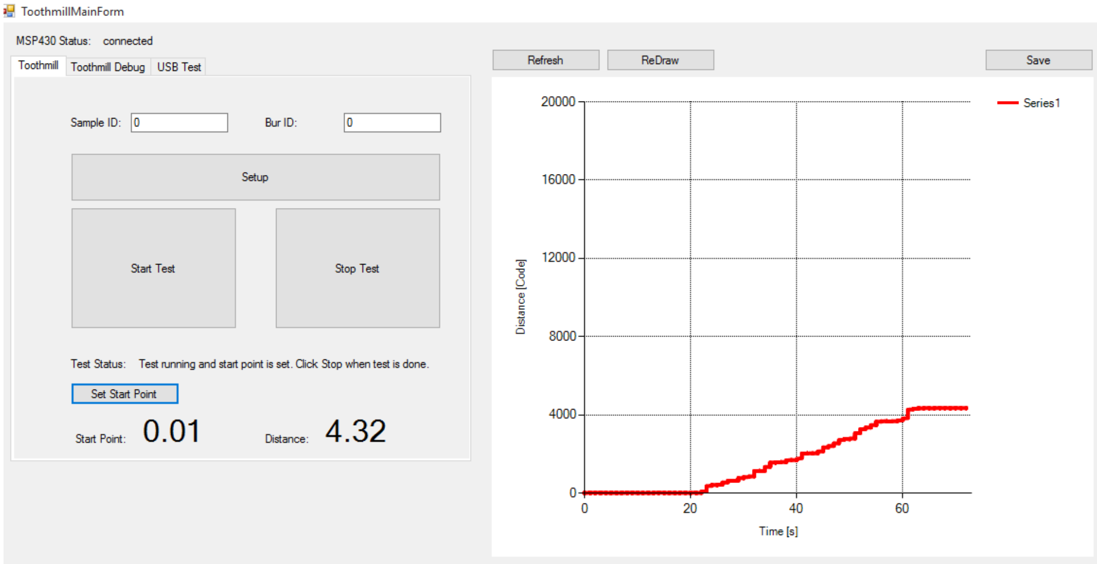


Figure 2: Software view when recording during cutting.

Figure 3: Lithium Disilicate (left) and Zirconia ingots (right).

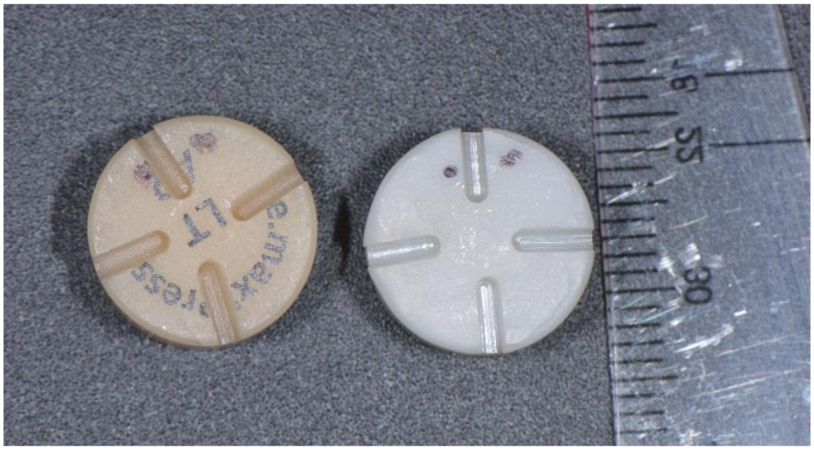


Figure 4: Samples showing 4 cuts

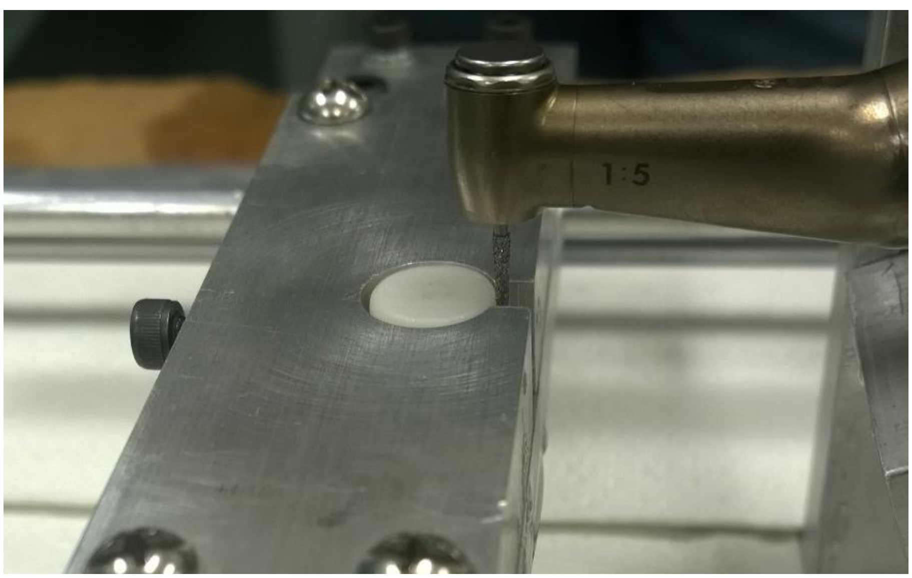


Figure 5: Contact of the sample and the bur, showing the perpendicular position of the bur toward the sample and the 2mm depth.

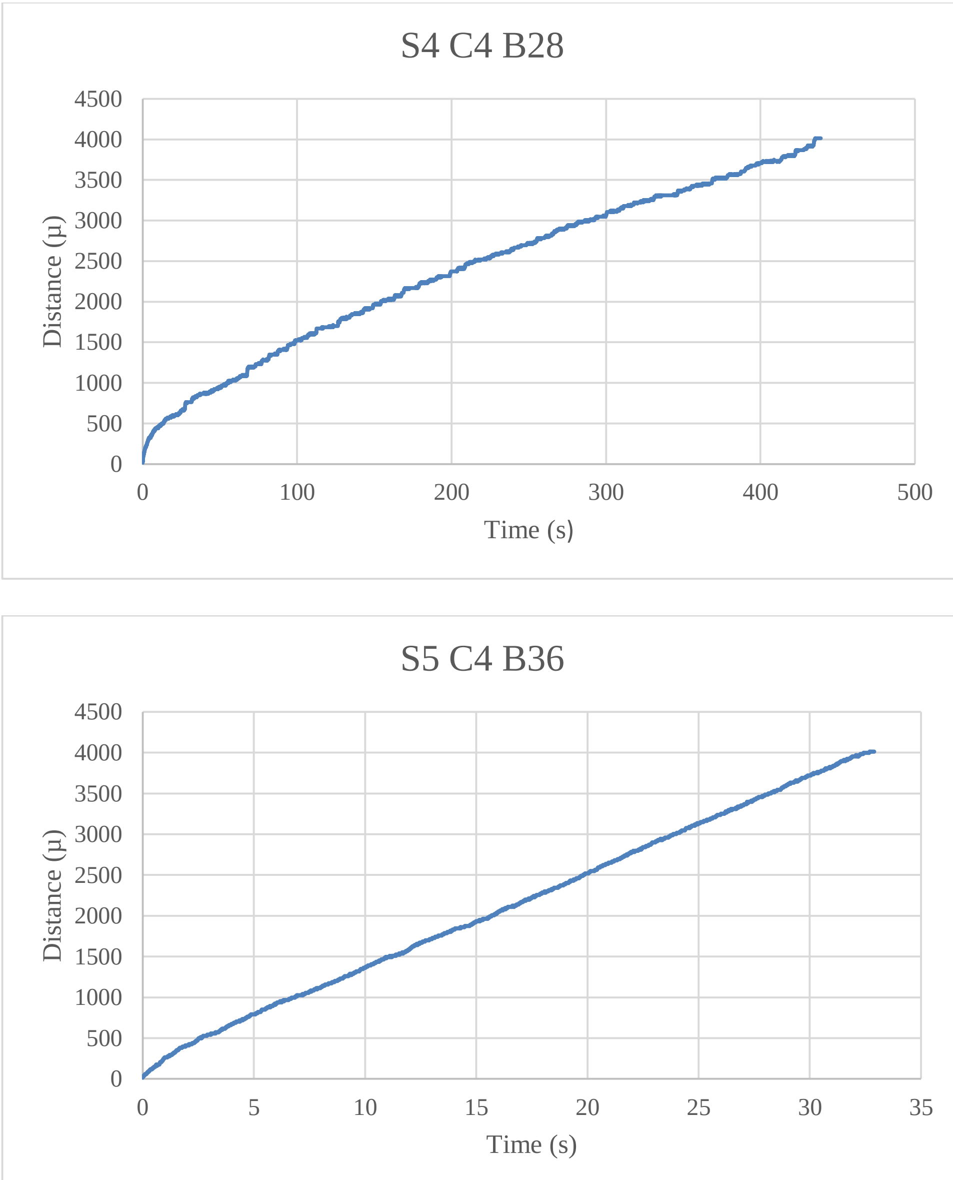
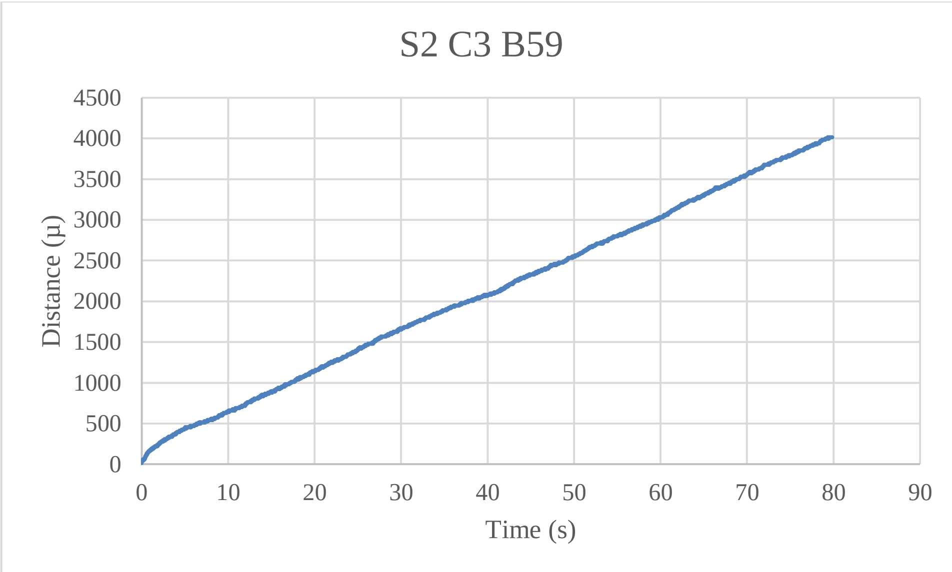


Figure 6: Examples of Zirconia block cut process in function of distance over time. S4 C4 B28 (Sample 4, Cut 4, Bur 28) longest cut. S5 C4 B36 (Sample 5, Cut 4, Bur 36) fastest cut.



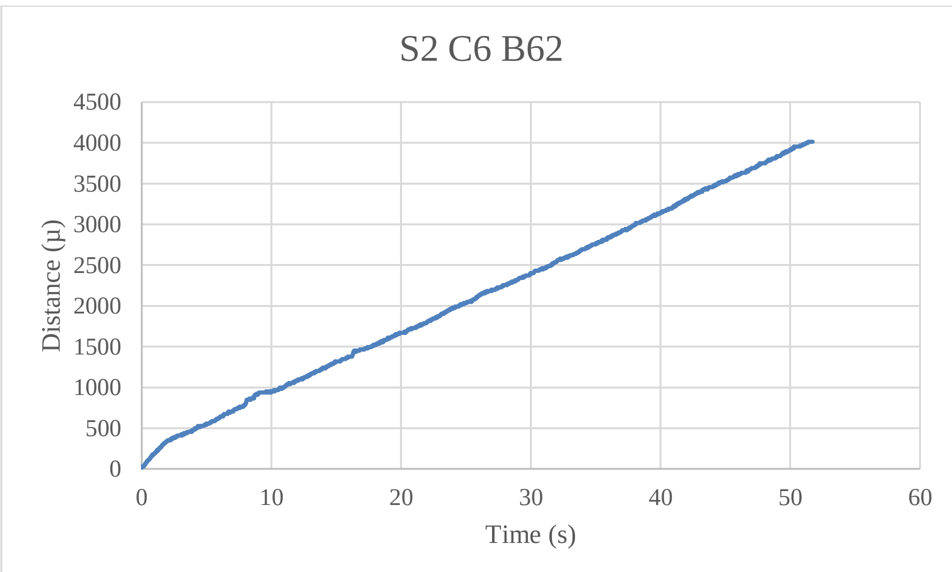


Figure 7: Examples of Lithium Disilicate block cut process in function of distance over time. S2 C3 B59 (Sample 2, Cut 3, Bur 59) longest cut. S2 C6 B62 (Sample 2, Cut 6, Bur 62) fastest cut.

APPENDIX B

TABLES

Table 1: Summary data from the cutting process

	# Cuts	# Burs	Distance	Time	Temperature	Mat Loss
Zirconia	46	46	4	150.00	71.95	0.06
L.D	46	46	4	38.48	72.81	0.03

L.D = Lithium Disilicate
Distance (mm), Time (s), Temperature (ºF), and Material Loss (gr)

Table 2. Descriptive statistics for time and temperature

		Zirconia				Lithium Disilicate			
		Temp 13	Temp 23	Time 13	Time 23	Temp 13	Temp 23	Time 13	Time 23
N	Valid	46	46	46	46	46	46	46	46
	Missing	0	0	0	0	0	0	0	0
Mean		-1.3348	-.0174	150.0000	120.0000	-1.3587	.0065	38.4783	8.4783
SD[a]		.90731	.60784	92.08692	92.08692	.83122	.24074	15.05064	15.05064
SE[b]		.13378	.08962	13.57747	13.57747	.12256	.03550	2.21910	2.21910
Median		-1.3	.0000	150.0000	120.0000	-1.3000	.0000	30.0000	.0000
Minimum		-3.6	-1.3	30.00	.00	-4.20	-.90	30.00	.00
Maximum		1.2	2.5	450.00	420.00	1.00	.70	90.00	60.00

Standard Deviation

Standard Error of Mean

Temp 13: Difference between initial temperatures to final temperature.

Temp 23: Difference between temperatures at the first 30s to final temperature.

Time 13: Difference between initial times to final time.

Time 23: Difference between times at the first 30s to final time.

Table 3. T-Test group statistics for time and temperature

		N	Mean	Std. Deviation	Std. Error Mean
Time 23	Zirconia	46	120.0000	92.08692	13.57747
	LD	46	8.4783	15.05064	2.21910
Temp 12	Zirconia	46	-1.3174	.72550	.10697
	LD	46	-1.3652	.75872	.11187
Temp 23	Zirconia	46	-.0174	.60784	.08962
	LD	46	.0065	.24074	.03550

Temp 13: Difference between initial temperatures to final temperature.

Temp 23: Difference between temperatures at the first 30s to final temperature.

Time 13: Difference between initial times to final time.

Time 23: Difference between times at the first 30s to final time.

Table 4. Independent sample test for time and temperature

		Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference t-test for Equality of Means	
		F	Sig.	t	df	Sig. (2-tailed)	Mean difference	Std. Error Difference	Lower	Upper
Time 23	Equal variances assumed	33.333	< .001	8.106	90	< .001	111.52174	13.75762	84.188982	138.85366
	Equal variances not assumed			8.106	47.402	< .001	111.52174	13.75762	83.85117	139.19231
Temp 12	Equal variances assumed	.367	.546	.309	90	.758	.04783	.15478	-.25967	.35532
	Equal variances not assumed			.309	89.820	.758	.04783	.15478	-.25968	.35533
Temp 23	Equal variances assumed	17.725	< .001	-.248	90	.805	-.02391	.09639	-.21542	.16759
	Equal variances not assumed			-.248	58.779	.805	-.02391	.09639	-.21681	.16899

Temp 13: Difference between initial temperatures to final temperature.

Temp 23: Difference between temperatures at the first 30s to final temperature.

Time 13: Difference between initial times to final time.

Time 23: Difference between times at the first 30s to final time.

Table 5: Correlation between time and temperature for Zirconia.

		Temp 13	Temp 23
Time 13	Pearson Correlation	-.487**	-.423**
	Sig (2-tailed)	.001	.004
	N	46	46
Time 23	Pearson Correlation	-.487**	-.423**
	Sig (2-tailed)	.001	.004
	N	46	46

** .Correlation is significant at the 0.01 level (2-tailed)

Temp 13: Difference between initial temperatures to final temperature.

Temp 23: Difference between temperatures at the first 30s to final temperature.

Time 13: Difference between initial times to final time.

Time 23: Difference between times at the first 30s to final time.

Table 6: Correlation between time and temperature for Lithium Disilicate.

		Temp 13	Temp 23
Time 13	Pearson Correlation	-.077	-.126
	Sig (2-tailed)	.613	.404
	N	46	46
Time 23	Pearson Correlation	-.077	-.126
	Sig (2-tailed)	.613	.404
	N	46	46

** .Correlation is significant at the 0.01 level (2-tailed)

Temp 13: Difference between initial temperatures to final temperature.

Temp 23: Difference between temperatures at the first 30s to final temperature.

Time 13: Difference between initial times to final time.

Time 23: Difference between times at the first 30s to final time.

Table 7. Descriptive statistics for material loss for Zirconia

		Weight 1	Weight 2	Weight 12
N	Valid	46	46	46
	Missing	0	0	0
Mean		6.7548	6.6929	.0619
SD[a]		.15752	.15702	.01593
SE[b]		.02274	.02266	.00230
Median		6.7600	6.6950	.0600
Minimum		6.39	6.30	.03
Maximum		7.04	6.98	.10

SD: Standard Deviation

SE: Standard Error of Mean

Weight 1: Weight before cutting

Weight 2: Weight after cutting

Weight 12: Difference between Weight 1 and Weight 2

Table 8. T-test one-sample statistics for Zirconia

	N	Mean	Std. Deviation	Std. Error Mean
Difference	46	.0619	.01593	.00230

Difference: Difference between Weight 1 and Weight 2

Table 9. One-sample test for Zirconia

	t-test for Equality of Means				95% Confidence Interval of the Difference t-test for Equality of Means	
	t	df	Sig. (2-tailed)	Mean difference	Lower	Upper
Difference	26.906	47	< .001	.06188	.0572	.0665

Difference: Difference between Weight 1 and Weight 2

Table 10. Descriptive statistics for material loss for Lithium Disilicate

		Weight 1	Weight 1	Weight 12
N	Valid	46	46	46
	Missing	0	0	0
Mean		2.8221	2.7900	.0321
SD		.07649	.07760	.0116
SE		.01104	.01120	.00168
Median		2.8150	2.7900	.0300
Minimum		2.68	2.65	.01
Maximum		2.97	2.93	.07

SD: Standard Deviation

SE: Standard Error of Mean

Weight 1: Weight before cutting

Weight 2: Weight after cutting

Weight 12: Difference between Weight 1 and Weight 2

Table 11. T-test one-sample statistics for Lithium Disilicate

	N	Mean	Std. Deviation	Std. Error Mean
Difference	46	.0321	.01166	.00168

Difference: Difference between Weight 1 and Weight 2

Table 12. One-sample test for Lithium Disilicate

	t-test for Equality of Means				95% Confidence Interval of the Difference t-test for Equality of Means	
	t	df	Sig. (2-tailed)	Mean difference	Lower	Upper
Difference	19.061	47	< .001	.03208	.0287	.0355

Difference: Difference between Weight 1 and Weight 2

Table 13. T-test group statistics for material loss

		N	Mean	Std. Deviation	Std. Error Mean
Weight 1	Zirconia	46	6.7548	.15752	.02274
	LD	46	2.8221	.07649	.01104
Weight 2	Zirconia	46	6.6929	.15702	.02266
	LD	46	2.7900	.07760	.01120
Weight 12	Zirconia	46	.0619	.01593	.00230
	LD	46	.0321	.01166	.00168

Weight 1: Weight before cutting

Weight 2: Weight after cutting

Weight 12: Difference between Weight 1 and Weight 2

Table 14. Independent sample test for material loss

		Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference t-test for Equality of Means	
		F	Sig.	t	df	Sig. (2-tailed)	Mean difference	Std. Error Difference	Lower	Upper
Weight 1	Equal variances assumed	23.879	< .001	155.597	94	< .001	3.93271	.02527	3.88252	3.98289
	Equal variances not assumed			155.597	67.998	< .001	3.933271	.02527	3.88227	3.98314
Weight 2	Equal variances assumed	19.360	< .001	154.386	94	< .001	3.90292	.02528	3.85272	3.95311
	Equal variances not assumed			154.386	68.665	< .001	3.90292	.02528	3.85248	3.95335
Weight 12	Equal variances assumed	4.429	< .001	10.454	94	< .001	.02979	.00285	.02413	.03545
	Equal variances not assumed			10.454	86.128	< .001	.02979	.00285	.02413	.03546

Weight 1: Weight before cutting

Weight 2: Weight after cutting

Weight 12: Difference between Weight 1 and Weight