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INFLUENCE OF CERAMIC BINDERS ON MECHANICAL PROPERTIES AND FINISHING OF GREEN MACHINED ALUMINA

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Abstract. *This paper deals with the analysis of the influence of different binders on green machining performance. The ceramic binder is responsible for promoting mechanical strength to the compacted piece during machining process; however, it can also harm the material removal due to clogging of the machining tool. The objective of this study is to analyze the behavior of four different binders on green peripheral cylindrical grinding. Alumina powders prepared with PVB, PVAl and two acrylics binders was formed as cylinders measuring 10 mm diameter and 55 mm length by isostatic pressing at 100 MPa. The green bodies were grinded by a 80 mesh alumina vitrified grinding wheel, dimensions being about 75 mm x 6 mm x 19 mm, model 38A80 IVH. The cutting parameters were 45 m/s cutting speed, 1 mm depth of cut, and 400 mm/min feed speed. The grinding process has applied an aerostatic dicing spindle (D05716/3) from LoadPoint Bearing Ltd. The sintered specimens were characterized concerning the surface finishing and mechanical strength by four point flexural strength test. The B-1007acrilic binder presented the highest flexural strength (316±25 MPa) and the lowest roughness (1.18±0.07 µm) the PVAl presented the best shrinkage value (15.69±0.27 %) and the lowest machining torque (0.019±0.003 N.m). These obtained information are important for decisions about the binder selection relative to the products performance requirements.*

Keywords: *ceramic, green machining, acrylic binder, mechanical resistance.*

1. INTRODUCTION

The industrial manufacture of ceramics products are mostly made from powders, which means that materials in their natural state (fine ceramic powder) are compacted, then sintered at high temperatures, and often machined to size and finishing required (Ng et al., 2006; Borger et al., 2002).

Although the technology of powder processing is widely used in many industries, know-how is needed to obtain products with high quality and low cost. For example, manufacturing processes can significantly influence the properties of advanced ceramics. For a given production method, the slightest change in the condition of the powder processing can cause a major difference in the quality of the ceramic product (Fortulan and Purquerio, 1998; Naito et al., 2010).

When the surface finishing, dimensional accuracy and shape are required machining is necessary. However, the machining of sintered ceramics consumes time and energy, and normally require specific equipments, such as tools with extreme hardness such diamond and high stiffness machine. Accordingly, this operation is very expensive and can represent up to 80 % of the cost of a ceramic part production (Desfontaines et al., 2005).

Alternatively, may be employed, before sintering, the green machining technique which is economical and up to 1000 times faster than ceramic sintered machining. Which can be done with almost all of the tools and techniques used in the metals and therefore are widely used in the manufacture of ceramic components. But its machinability depends on many factors such as mechanical strength, resistance to chipping, and uniform density (Desfontaines et al., 2005; Lindqvist and Carlstrom, 2002; Bortzmeyer et al., 1993; Prabhakaran et al., 2001; Birkby et al., 1994; Sheppard, 1992).

Although high green strength is a desired property when performing green machining, parts with extremely high green strength also gain fragility. This makes difficult conventional operations such as drilling, milling, and turning. Conventionally, plasticizers are added to reduce the brittle nature and improve the machining characteristics of the green ceramic (Prabhakaran et al., 2001, p 185; Birkby et al., 1994; Sheppard, 1992). Some studies have reported that low mechanical strength allowed a better machinability, but only until the handling of the compacted is possible (Nunn and Kirby, 1996; Birkby et al., 1994). It was also observed that the difference in mechanical strength results in different behaviors of cutting and fracture, leading to transgranular or intergranular fracture of the green compacted (Desfontaines et al., 2005; Birkby et al., 1994).

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Researches in green machining of ceramics are rare and know-how is mainly empirical. One of the most critical points to be investigated is the characterization of machinability of green parts. Industries build on the experiences, being very difficult to predict the resistance to machine a green piece and what is the best strategy to accomplish the work (Desfontaines et al., 2005).

The removal of surface and sub-surface defects as well as the correction of deformities, due to non-uniform density obtained in the forming process, may be a strategy to a decisive recommendation by green machining. This machining performed in conjunction with the conformation can simplify process and forming molds (Bukvic, 2011).

Binder is the most important additive in the ceramic pressing and in the spray-drier granulation process. It plays a great influence on the properties of ceramic granules as apparent density, flow rate and compression behavior. Binders are typically long-chain polymers which provide the primary function to promote the green strength of a compacted ceramic body, forming bridges between the particles. A good binder should promote the green strength to a low amount added in the ceramic powder. In some forming methods, it also promotes plasticity that helps the forming process (Kumar et al., 2000).

In the work carried out by Ander et al. (1997), it was requested that the binder should provide to a compacted body, which are: high green mechanical strength of the body, reduced brittleness, small deflection of the green body, easy variability of its properties, low amount added to the mixture and possibility of green machining.

Binders such as poly (vinyl alcohol) (PVAl) and poly (ethylene glycol) (PEG) provide mechanical strength within 1 MPa, once they do not have a strong interaction between its molecules. Already acrylic binder consists of carboxylic acid groups that interact strongly with the ceramic powder. The hydrogen connections between chains also result in strong interaction between its molecules. This binder has been developed by Rohn and Haas Co. for application on green machining, allowing green strength higher than 6.5 MPa (Sheppard, 1999).

The green strength of a ceramic material increases linearly with increasing amount of binder added to the ceramic mixture (Kumar et al. 2000), performing a role in the green machining. Binder formulation should be thought to not allow part chipping and breaking, while, at the same time, a tool removes material with a rapid material removal rate (Sheppard, 1999).

During green machining, the binder adhesion can occur in the abrasive wheel pores or in the cutting tool grooves, which can cause loss of product mechanical properties. This can be avoided by proper selection of the tool grain size, porosity or groove. The binder can also be removed by cleaning methods such as sandblasting to promote a new and clean abrasive surface (Sheppard, 1999).

In this work was performed the study of the influence of different binders in the green machining performance of alumina. A tangential cylindrical grinding was applied to obtain green cylindrical specimens with the measurement of machining torque. After sintering, the samples were evaluated according linear shrinkage, surface roughness and mechanical resistance by four points flexural strength test evidencing the better binder.

2. MATERIALS AND METHODS

For the experiment was elaborated a content composition with an equalitarian binder concentration of 2 wt% with deflocculant and lubricant (Table 1). The green machining performance was analyzed by the torque measurement confronted with the four points flexural strength test after sintering.

Table 1 – Formulations of the prepared ceramic powder slurry.

<table>
<tr><th>Formulation</th><th>Binder (2 wt%)</th><th>Deflocculant (1 wt%)</th><th>Lubricant (0.5 wt%)</th><th>Solution</th></tr>
<tr><td>A</td><td>PVAL</td><td>Ammonium Polyacrylate</td><td rowspan="4">Ethylene glycol</td><td>Distilled Water</td></tr>
<tr><td>B</td><td>PVB</td><td>---</td><td>Isopropyl Alcohol</td></tr>
<tr><td>C</td><td>B-1022</td><td>D-3005</td><td>Distilled Water</td></tr>
<tr><td>D</td><td>B-1007</td><td>D-3005</td><td>Distilled Water</td></tr>
</table>

The raw material for the specimens was calcined alumina A1000-SG (Almatis, Inc.), equivalent average particle diameter of 0.4 μm, surface area of 7.7 mm^2/g, and ρ_{real} of 3.99 g/cm^3. The formulations of slurries were described in Tab. 1, the slurry was composed with volume relation 70/30 liquid/solid, respectively. Each formulation were wet-mixed in ball mill for 12 hours, after dried with air flow heat gun at temperature around 80ºC, the ceramic agglomerates were manually granulated until passing through a 80 mesh (180 μm) sieve.

Cylindrical blanks with approximate dimensions of Ø11x55 were isostatically pressed at 100 MPa, obtaining 5 pieces of each formulation. These were heat treated at 100 ºC for 12 hours, to homogenize and relieve compacting stress (Margarido 2012). The blanks were attached by one of its sides into a metallic support applying a thermal adhesive. The support was fixed on headstock for machining operation.

The green blanks were then machined to a cylindrical shape, in the dimensions of Ø7x45 mm according to the schedule shown in Tab. 2. These were experimental data from Margarido (2012).

ISSN 2176-5480

Table 2 – Parameters applied in the machining experiments.

Formulation	**Tool material**	**Depth of cut (a_p) (mm)**	**Feed speed (v_f) (mm/min)**	**Removal rate (Q) (mm^3/min)**
A B C D	Electro-fused Alumina	1.0	400	10,000

The machining trials were performed using a computer numerical control (CNC) cylindrical grinding machine equipped with a dicing spindle (D05716/3) with aerostatic bearing from LoadPoint Bearing Ltd., rotating at 11,400 rpm; providing a peripheral cylindrical grinding. As cutting tool was used a alumina electro-fused (80 mesh) grinding wheel with vitrified bond (38A80 IVH) from Norton Saint-Gobain Ltd., at the dimensions of 75 mm x 6 mm x19 mm that generated a cutting tool speed of 45 m/s.

To measure the machining torque was used a torque sensor (MKDC-5) with maximum capacity of 5.0 N.m from MK Control and Instruments Ltd., which was coupled between the specimen and a servo motor (WEG SWA56-2.5-20) with servo drive (WEG SCA050004) from WEG Ltd.. The data sent by the torque sensor were acquired by a data acquirement (USB 6009 - 14-bit resolution) from National Instruments Ltd. The servo-motor and torque sensor was controlled by Labview software interface from National Instruments Ltd. The purpose of the servo motor is to rotate the specimen, to the material be removed by the grinding wheel and forming a circular profile. The rotation of the servo motor was set at 600 rpm. When fired up, was scheduled to gain rotation gradually, to avoid the risk of breaking the blank.

The assembly of the bench test is shown in Fig. 1. The planning and execution of the green machining are shown in Fig. 2.

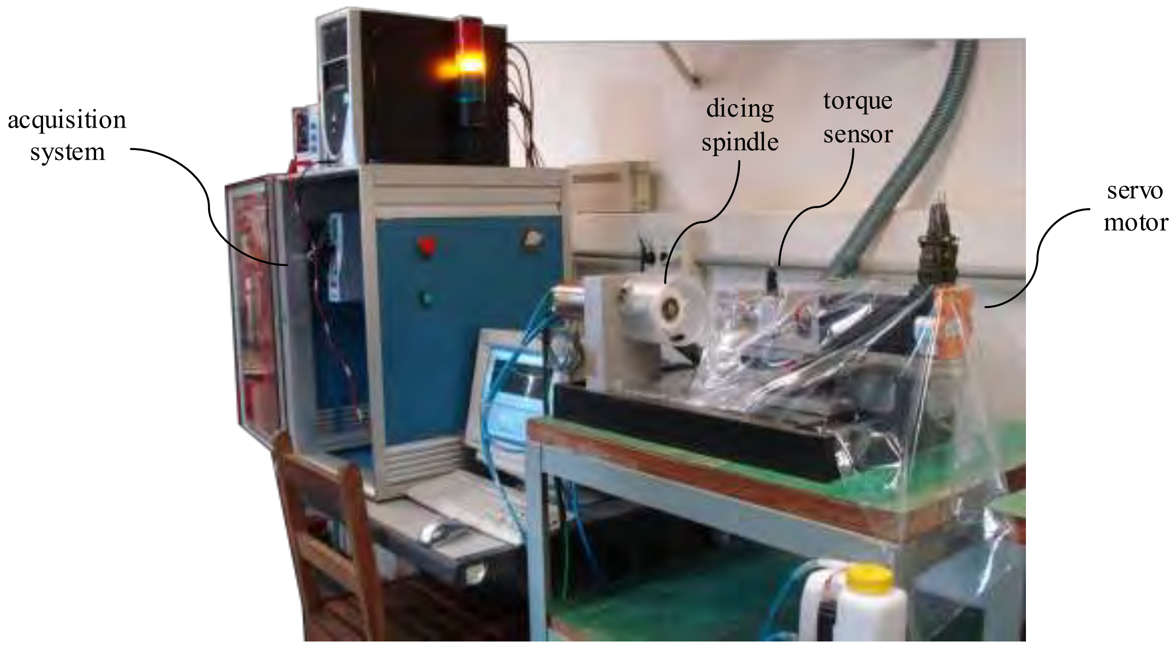

Figure 1 – Image of machining bench test.

The green machined cylinders were sintered at 1600 ºC and subjected to the four point flexural strength test, and had their machined surfaces analyzed by surface roughness.

The following heating rates were used in the sintering process: room temperature to 300 °C (2 °C/min), 300 °C to 600 °C (3 °C/min), 600 °C to 1200 °C (5 °C/min), 1200 °C to maximum temperature (6 °C/min), holding at the maximum temperature for 2 h, followed by cooling to room temperature inside the furnace.

The analysis of four point flexural strength test followed ASTM standard C1684-08, considering the approximate specimens dimensions after sintering of Ø6x40 mm. The machine used was a Bionix® Servohydraulic Test Systems (370.02) from MTS Ltd., traverse speed of 0.2 mm/min, load cell of 150.0 kN and applied span of 20.0 mm.

The surface roughness was measured on a portable roughness tester (Surtronic 3+) from Taylor Robson Co., using Gausseano filter, Cutoff (Lc) of 0.8 mm and database length of 4.0 mm for the measurement of the arithmetic average roughness (Ra).

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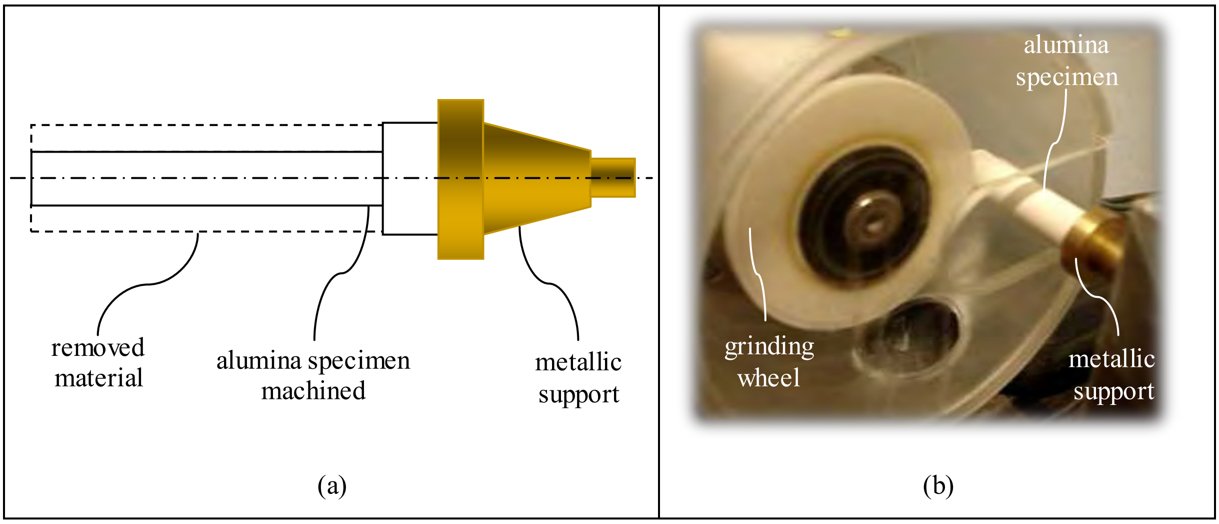

Figure 2 – Specimens machining operation: (a) planning e (b) execution.

3. RESULTS AND DISCUTION

After the machining procedure, an analysis of the specimens showed the influence of the binder on the edge chipping effect, appointed by the circled region observed in Fig. 3. It can be seen that the formulation using PVAl binder showed the highest edge chipping, followed by PVB, B-1022 and ending with B-1007, which had less chipping. Defects of this nature could be responsible by the binder low shearing resistance and cause product lower finishing due to intergranular fracture, which may lead to the discard if not reach project requirements.

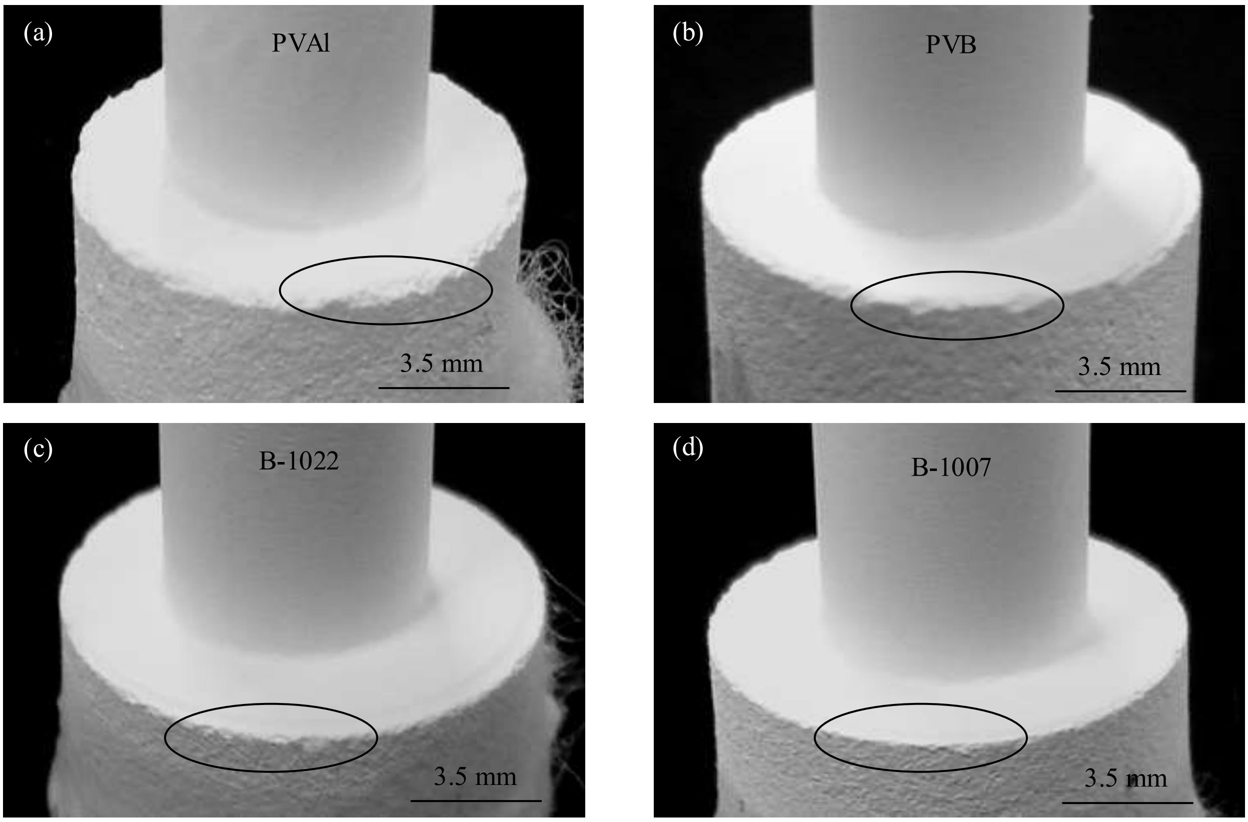

Figure 3 – Images of edge chipping after green machining: (a) PVAl binder; (b) PVB binder; (c) B-1022 binder; (d) B-1007 binder.

ISSN 2176-5480

The specimens linear shrinkage calculation (Figure 4) showed the lowest value observed for the formulation with the PVAl binder (15.69±0.27 %) followed by B-1022 (16.02±2.08 %), B-1007 (16.03±0.12 %), and obtaining the largest value for the PVB binder (18.30±1.60 %). The lower the value observed smaller size reduction was experienced by piece. In this case the specimens which least shrank were with the PVAl binder and those that suffered the most shrank were with PVB binder, demonstrating that PVAl is more effective, permitting higher compactation rate which leads to lower shrinkage. The acrylic binder had values very close to PVAl, proving to be equally effective.

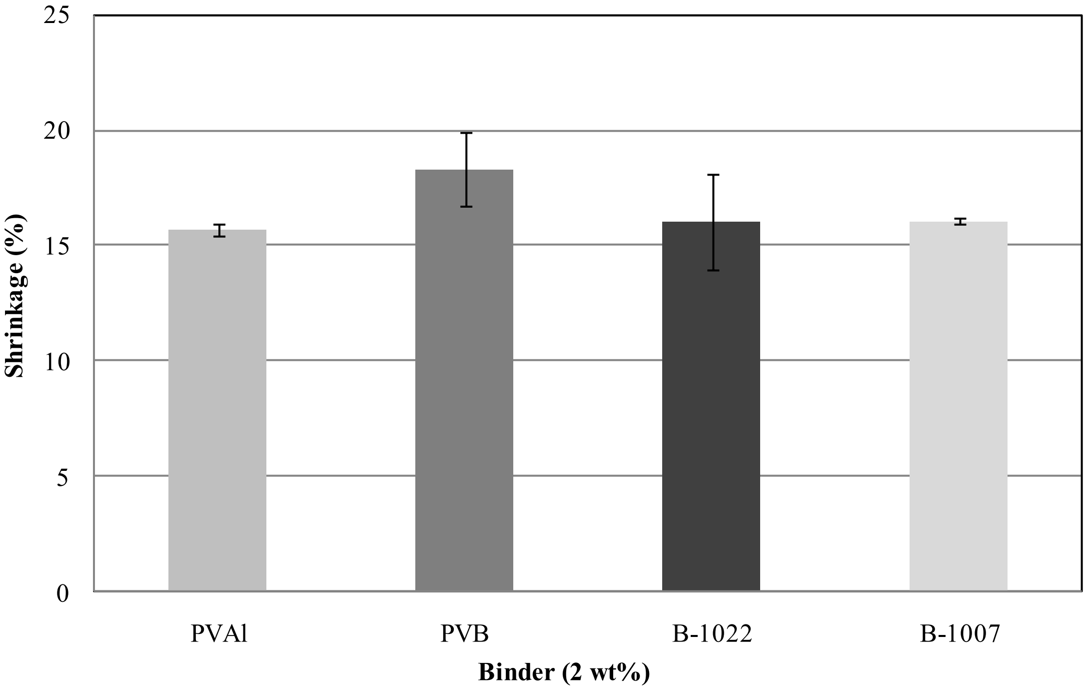

Figure 4 – Graphic of linear shrinkage.

Torque values were obtained from the 5 largest torque peaks observed during the machining process. These peaks were considered to be responsible for the introduction of some defect into the piece. Considering that the blank had a diameter of approximately 11 mm, and the machined specimen with a diameter of approximately 7 mm, furthermore, a depth of cut of 1 mm applied. It was necessary two passes of the grinding wheel to obtain the specimen. However, higher peaks values were observed in the first pass of the tool when the workpiece reached a diameter of 9 mm.

Figure 5 demonstrated the influence of the binders on the machining torque measurement. The lowest torque value was observed for the PVAl binder (0.019±0.003 N.m), followed by the PVB (0.022±0.005 N.m), B-1007(0.025±0.003 N.m) and the highest value being obtained for the acrylic binder B-1022 (0.027±0.005 N.m). Thus, greater effort was needed for the machining of acrylic binders compared to PVB and PVAl, which could be explained by a higher green mechanical resistance provided by the binder.

Binder influence on the surface roughness demonstrated opposite response compared to the torque, which showed lower values for the acrylic binders, lowest to B-1007 (1.18±0.07 μm) followed by B-1022 (1.41±0.10 μm). The highest surface roughness was then observed for the PVAl (1.87±0.13 μm) and PVB (1.72±0.46 μm) with an amount right below, as seen in Fig. 6, demonstrating that the acrylic binders provide better surface finishes. High green mechanical and shearing resistance could be responsible by a transgranular facture that permits lower values of surface finishing of the acrylic binders.

Regarding the loss of mechanical properties, Fig. 7 shows the influence of binders on the maximum flexural strength. Highest strength value was observed for the acrylic binder B-1007 (316±25 MPa), followed by B-1022 (274±14 MPa), PVB (268±49 MPa), while the lowest value was observed for the PVAl binder (187±5 MPa), which demonstrate the best performance to the acrylic binders.

Ceramic has the fragility as its negative characteristic, added to its static fatigue. To improve quality and reliability to mechanical strength, the surface finishing and absence of critical defects are decisive. Given a fixed 2 wt% binder amount in the powder, acrylic binders were those who had better responses in terms of surface roughness and maximum rupture stress. While they require a higher machining torque, there was no prejudice to the mechanical property.

Emphasis is then assigned to the acrylic binder B-1007, which showed the best results in terms of mechanical strength and surface roughness, without presenting the highest torque to be machined (the largest being required for the B-1022).

ISSN 2176-5480

However for PVAl binder, which provided less shrinkage and less machining torque, had the lowest strength and the worst surface roughness. In principal indicates that PVAl offers less shearing resistance, what allowed intergranular fracture, showed on Fig. 3a, where was observed pronounced edge fracture.

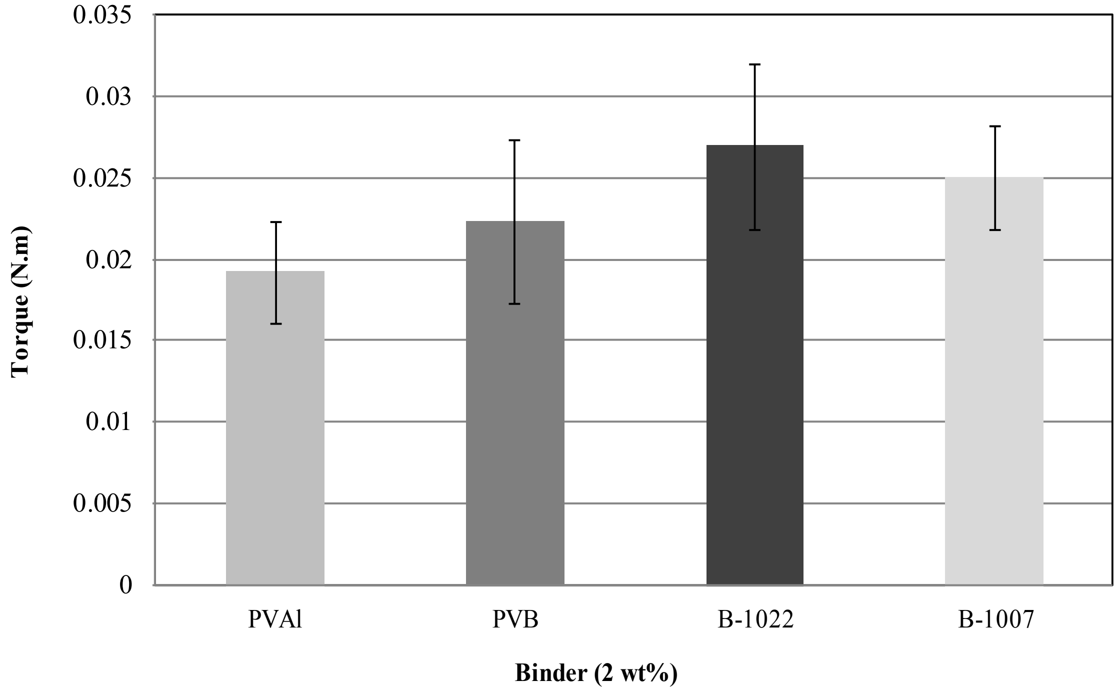

Figure 5 – Graphic of machining torque.

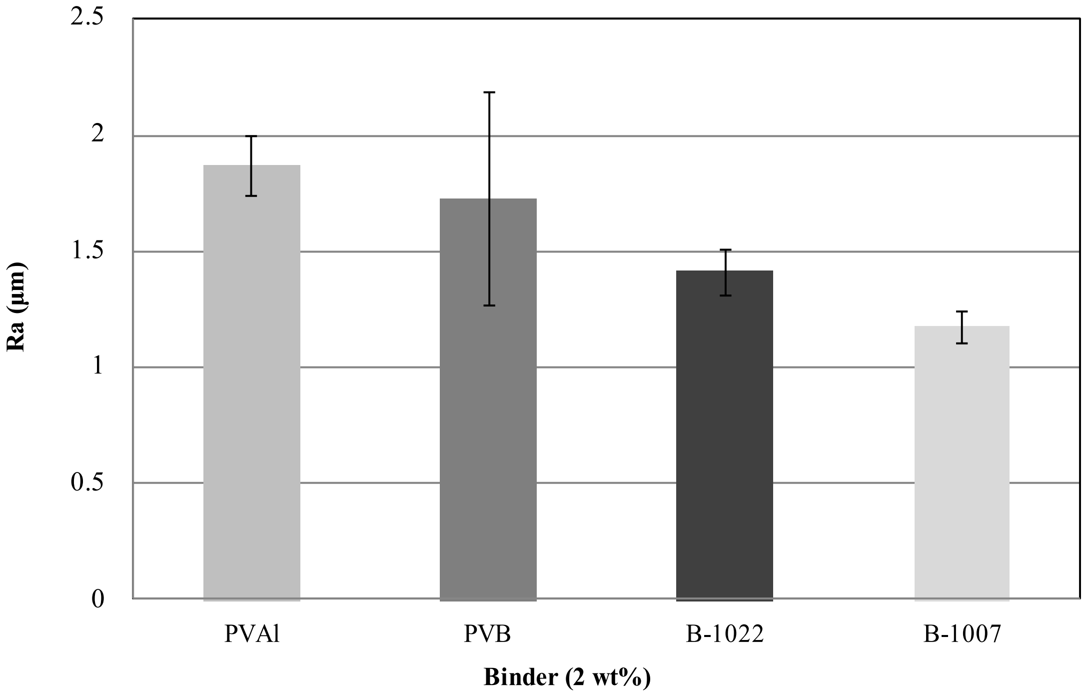

Figure 6 – Graphic of arithmetic overage surface roughness.

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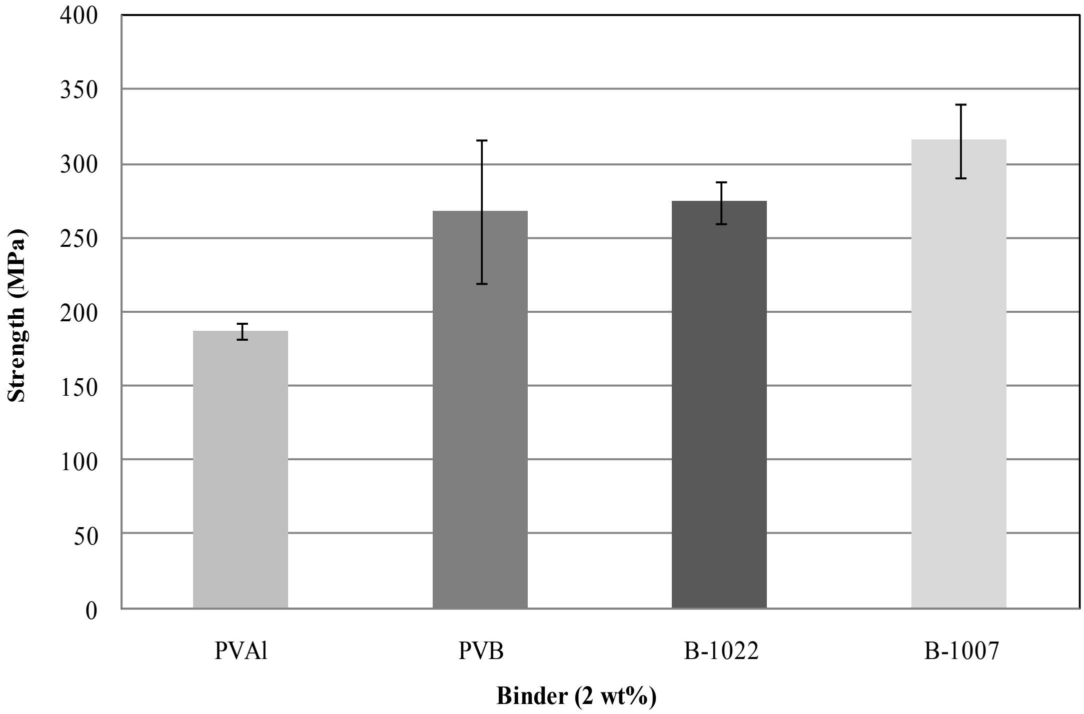

Figure 7 – Graphic of maximum flexural strength.

4. CONCLUSIONS

The present study showed strong effects of ceramic binder on mechanical properties and finishing of sintered alumina samples. The behavior of the binders during green machining showed aspects of the mechanism of removal ranging from intergranular to transgranular that influences the mechanical resistance and surface finishing. The acrylic B-1007 binder demonstrated favorable results to flexural strength (316±25 MPa) and roughness (1.18±0.07 µm). The PVAl binder present the best value for machining torque (0.019±0.003 N.m) and shrinkage (15.69±0.27 %), the PVB and acrylic B-1022 binders in general presented intermediate values. The mechanical gain achieved due to the binder was near 70% for the extremes, although its selection and decision is dependent of product requirements and manufacture available. These results can be used as a guide to the decisions in a manufacture planning.

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