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INFLUENCE OF PRODUCTION PARAMETERS ON THE ROUGHNESS OF ORTHODONTIC ABS MODELS MANUFACTURED VIA ADDITIVE MANUFACTURING

INFLUÊNCIA DOS PARÂMETROS DE PRODUÇÃO NA RUGOSIDADE DE MODELOS ORTODÔNTICOS DE ABS FABRICADOS VIA MANUFATURA ADITIVA

INFLUENCIA DE LOS PARÁMETROS DE PRODUCCIÓN EN LA RUGOSIDAD DE LOS MODELOS DE ORTODONCIA EN ABS FABRICADOS MEDIANTE FABRICACIÓN ADITIVA

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ABSTRACT

Additive manufacturing (AM) has a strong impact in the dental field, offering advantages in productivity, cost, and customization of various products. Among the AM techniques, fused deposition modeling (FDM) has great application in the production of orthodontic molds (OM) compared to traditional techniques. However, the roughness of OM (orthodontic molds) produced by FDM is higher when compared to the pieces obtained through alginate molding. Therefore, evaluating the influence of FDM manufacturing parameters on roughness is of great importance. For this purpose, the experimental design methodology was used with the aim of determining which factors have a significant effect on OM roughness. Among the results obtained, layer height (LH) is the most influential factor in the roughness of the incisor element. For the canine and molar elements, the extruder nozzle diameter (END) is the most influential factor in roughness with an interaction between END and LH. Therefore, to aim for better roughness control in OM produced via AM, parameters such as layer height, extruder nozzle diameter, and filling percentage should be controlled.

RESUMO

A manufatura aditiva (MA) apresenta forte impacto na área odontológica oferecendo vantagens na produtividade, custo e customização de diversos produtos. Entre as técnicas de MA, a Fused Deposition Modeling (FDM) tem grande aplicação na produção de moldes ortodônticos (MO) quando comparada às técnicas tradicionais. Entretanto, a rugosidade dos MO produzidos por FDM são maiores quando comparados às peças obtidas por moldagem com alginato. Dessa forma, a avaliação da influência dos parâmetros de fabricação via FDM sobre a rugosidade é de grande importância. Para isso, a metodologia de delineamento de experimentos foi utilizada com o objetivo de verificar quais fatores exercem efeito significativo na rugosidade de MO. Entre os resultados obtidos, a altura da camada (AC) é o fator de maior influência na rugosidade do elemento incisivo. Para os elementos canino e molar, o diâmetro do bico extrusor (DBE) é o fator de maior influência na rugosidade com interação entre o DBE e a AC. Assim, ao se objetivar o melhor controle da rugosidade em MO produzidos via MA, deve-se controlar parâmetros como altura da camada, diâmetro do bico extrusor e porcentagem de preenchimento.

RESUMEN

La fabricación aditiva (FA) tiene un fuerte impacto en el campo odontológico, ofreciendo ventajas en productividad, costo y personalización de diversos productos. Entre las técnicas de FA, el modelado por deposición fundida (MDF) tiene una gran aplicación en la producción de moldes ortodónticos (MO) en comparación con las técnicas tradicionales. Sin embargo, la rugosidad de los MO producidos mediante MDF es mayor en comparación con las piezas obtenidas a través de la moldura de alginato. Por lo tanto, es de gran importancia evaluar la influencia de los parámetros de fabricación a través de MDF en la rugosidad. Con este fin, se utilizó la metodología de diseño experimental con el objetivo de determinar qué factores tienen un efecto significativo en la rugosidad de los MO. Entre los resultados obtenidos, la altura de capa (AC) es el factor más influyente en la rugosidad del elemento incisivo. Para los elementos canino y molar, el diámetro de la boquilla extrusora (DBE) es el factor más influyente en la rugosidad con una interacción entre DBE y AC. Por lo tanto, para lograr un mejor control de la rugosidad en MO producidos mediante FA, se deben controlar parámetros como la altura de capa, el diámetro de la boquilla extrusora y el porcentaje de llenado.

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INTRODUCTION

Additive manufacturing (AM) is a process that allows the conversion of digital models into physical models through a layer-by-layer printing or deposition process. Several industrial segments such as defense, aerospace, art, medicine and design are adopting additive manufacturing for customization and rapid production of products (Gibson et al., 2015; Volpato, 2017). Amorim (2022), Ferriotti et al. (2021), Cavaignac et al. (2020) and Abreu & Souza (2019) reinforce the potential of this technology to be fully exploited, mainly in new ways of designing products that accompany this development, given that the possibilities are too vast to be achieved only in the determination of the manufacturing process. Currently, there are several applications in the field of dentistry in which it is possible to manufacture personalized models (Amir et al., 2016; Vasconcelos et al., 2018).

Additive manufacturing has been adopted in dentistry at an increasing rate and the construction of dental models is one of the main applications of the technology used in the production of prostheses, orthodontics, implantodontics and oral and maxillofacial surgery, among others (Jaber et al., 2020; Yoo et al., 2021; Javaid & Hallem, 2019).

An essential prerequisite of the dental models is to create an accurate replica of the teeth and the surrounding tissues to serve the intended purposes. These models assist in diagnosis and restoration for evaluation, treatment planning and manufacturing of various dental appliances and prostheses. Currently, replicas of plaster poured into conventional molds (for example, alginate silicones, polysulfides, ethers) are considered the “gold standard” material for dental construction (Hyung et al., 2016; Jumyung et al., 2017).

The precision of the resulting models depends on several factors that may introduce errors. This includes data acquisition and image processing of the oral hard and soft tissues, and the myriad of parameters involved in the manufacturing and post-processing processes. However, the models obtained through polymerization in vat and material are prone to dimensional alterations during the polymerization phase and may show surface imperfections due to the stratification technique used in construction. The models also exhibit dimensional alterations in the post-processing process as they develop (Liu & Shin, 2019; Mohsen, 2017; Barone et al., 2019).

Melo & Peruchi (2021) suggest that one of the biggest challenges faced during the additive manufacturing process is to ensure that the dimensional specifications established during the elaboration of the project are reproduced with the lowest level of possible variation. To verify this dimensional accuracy, the authors analyzed the effects of six operational parameters – raster, layer height, density filling, coating angle, orientation and printing speed. The experimental study was carried out from a fractionated factory shoot and by means of the response surface methodology (RSM) with the objective of identifying the most significant operational input parameters for the response variation variations in compression, thickness and depth, and also for obtaining important information regarding the complex dependence of the quality properties of the process in relation to the input

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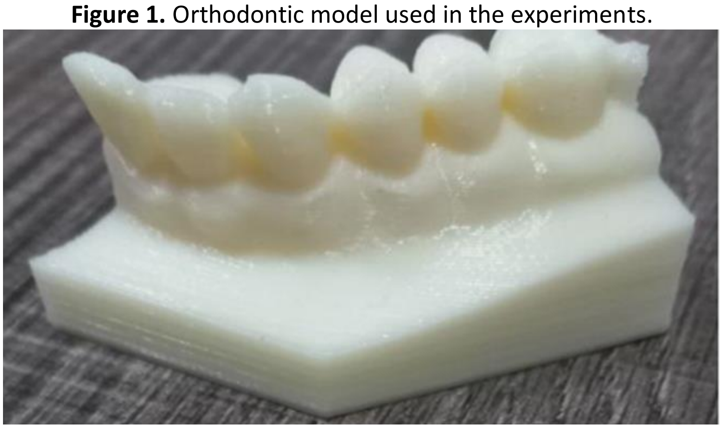
operational parameters. Following these dimensional questions, but addressing production conditions and care, the objective of this work was to identify which factor or factors have the greatest influence on roughness, mass and production time of orthodontic models in acrylonitrile - butadiene - styrene (ABS) via Fused Deposition Modeling (FDM).

METHODOLOGY

Typodontes™ model was used, which has great application for students and dental professionals in carrying out pre-clinical practices and not developing theoretical knowledge of anatomy.

In the reproduction in Figure 1, intraoral scanner from the iTero™ brand was used, obtaining an exact copy of the model with the possibility of reproducing it numerous times with the same quality. To maximize the production of the various samples, the upper quadrant directly of the orthodontic model was equipped to offer the anatomical details that can represent all the geometries of the complete model.

Figure 1. Orthodontic model used in the experiments.



It was used in additive manufacturing technique via Fused Deposition Modeling (FDM), for the production of samples. The filament used for the study was acrylonitrile-butadiene-styrene (ABS) with a diameter of 1.75mm in white. The equipment used was the Sethi – Model S3, ™ which presents a useful working area of 270 x 270 x 320 mm. The resolution can be adjusted in all settings (X, Y and Z) from 50 to 300 microns. The filament feeding speed was 150 mm/s and the dual extruder movement speed was 300 mm/s. It was used at a temperature of 110 °C on the equipment table.

The experimental outline was carried out with three factors on two levels, with two replicas and a central point. The evaluated factors are: diameter of the extruder; layer height deposited; and sample preparation, Table 1. The influence of the factors used in the design was analyzed for the varying responses: production time, mass of each sample and roughness. All statistical analyzes were performed using Minitab™ software.

Table 1. Parameters and levels adopted during sample production.

Fator	Level (Minimum)	Level (Maximum)
Extruder Nozzle Diameter (mm)	0,2	0,6
Layer Height (mm)	0,1	0,4
Sample Filling (%)	40	80

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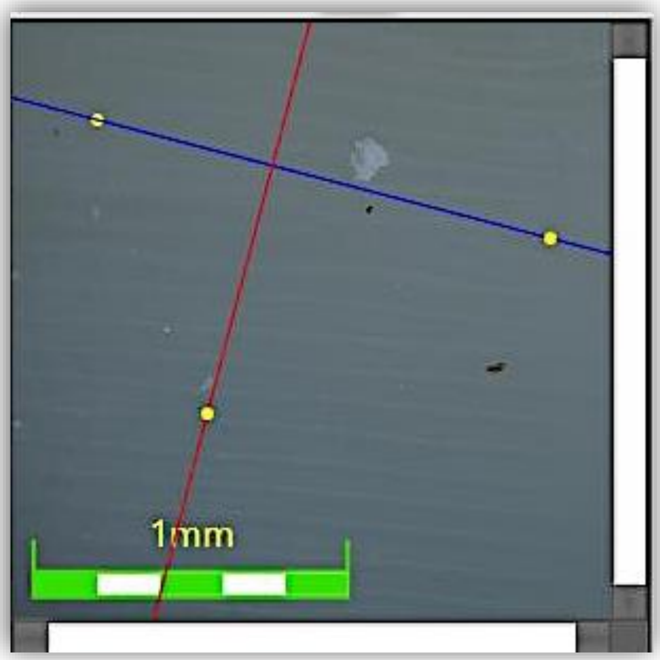
The quantification of the production time of each sample was measured using the FDM equipment itself and includes only the deposition time of the layers. The table heating time, adjustment of the extruder and any other processing parameters were not measured.

The mass quantification of each sample was carried out after the production of orthodontic models. The measurements were made by an analytical balance of the Shimadzu™ brand, with a precision of 0.1 mg.

The quantification of the roughness was carried out in the Arotec industry laboratory, using an Olympus digital microscope, model DSX 1000™ with a 10X objective lens. The roughness measurement was followed by the amplitude parameter (peak and value) in accordance with the ISO 4287:1997 standard and was measured at the average roughness (Rc), observed in Figure 2, the microscope image during the roughness measurements of the samples.

Figure 2. Microscope image during sample roughness measurements.



To analyze the roughness, three different dental elements with different anatomical shapes, volume and geometry are selected. Were selected the incisor, canine and first molar elements. The roughness measurement of the incisor and canine elements was carried out along the central line of the element, not in the direction of the length of the crown and between the cervical and incisal edge. For the first molar, a linear roughness measurement was performed along the crown and between the cervical and incisal edge of the mesial cusp.

RESULTS AND DISCUSSION

The results used in the experimental design are described in Table 2. From these data, the design and formatted regression models were developed, which are presented in Table 3.

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The model developed to identify the influence of the factors studied on the production time of each sample has the value of R^2, adjusted R^2 and predicted R^2 equal to 100%. For the generated model that identifies the most influential factors for the mass of each sample, the value of R^2 equals to 99.92%, adjusted R^2 equals to 99.84% and predicted R^2 equals to 99.61%.

For the generated model that identifies the most influential factors for the roughness of the incisor element, the value of R^2 equals to 99.67%, adjusted R^2 equals to 99.31% and predicted R^2 equals to 98.35%. For the roughness model of the canine element, the value of R^2 is equal to 98.89%, adjusted R^2 equals to 97.65% and predicted R^2 equals to 94.40%. For the roughness model of the molar element, the value of R^2 equals to 97.11%, adjusted R^2 equals to 93.85%, and predicted R^2 is equal to 85.35%.

Table 2. Results of two experiments used in the experimental design.

Order	Extruder Nozzle Diameter (mm)	Layer Height (mm)	Sample Filling (%)	Time (min.)	Volume (g)	Roughness Rc (µm)		
						I*	C*	M*
01	0,4	0,25	60	72	16,893	2,088	1,648	1,643
02	0,4	0,25	60	72	16,889	2,163	1,498	1,435
03	0,6	0,10	40	106	12,627	3,342	1,789	2,276
04	0,6	0,40	40	28	11,894	3,579	0,883	1,283
05	0,6	0,10	80	149	20,545	2,649	1,600	1,775
06	0,6	0,10	40	106	12,557	3,672	1,598	2,587
07	0,6	0,40	80	38	18,388	3,091	0,672	0,676
08	0,6	0,40	40	28	11,894	3,663	0,899	1,528
09	0,6	0,40	80	38	18,424	3,291	0,867	0,841
10	0,6	0,10	80	149	20,895	2,352	1,852	1,556
11	0,2	0,40	80	97	16,562	3,484	2,807	2,904
12	0,2	0,40	40	67	10,859	7,779	1,400	1,723
13	0,2	0,10	80	370	21,286	2,243	1,950	1,688
14	0,2	0,40	80	97	16,442	3,547	2,600	2,702
15	0,2	0,10	80	370	21,886	2,257	1,850	1,698
16	0,2	0,40	40	67	10,798	7,998	1,400	1,825
17	0,2	0,10	40	255	12,632	2,243	1,950	1,687
18	0,2	0,10	40	255	12,567	2,425	1,988	1,697

Note**:** I*-Incisive dental element; C*-Canine dental element; M*- Molar dental element.

Table 3. Results of the experimental design.

Response	S	R^2	R^2 Adjusted	R^2 Foretold
Production time	0	100,0 %	100,0 %	100,0 %
Volume of Each Sample	0,155	99,92 %	99,84 %	99,61 %
Incisor Roughness	0,143	99,67 %	99,31 %	98,35 %
Canine roughness	0,087	98,89 %	97,65 %	94,40 %
Molar Roughness	0,142	97,11 %	93,85 %	85,35 %

It is observed in Figure 3 that the factor of layer height (AC) is the most influential factor in the production time of the samples. The diameter of the nozzle extruder (DBE) and the sample prefill (PA) also have an influence. As the values used for these parameters are increased, the production time is reduced. It is also observed that the central point offers an

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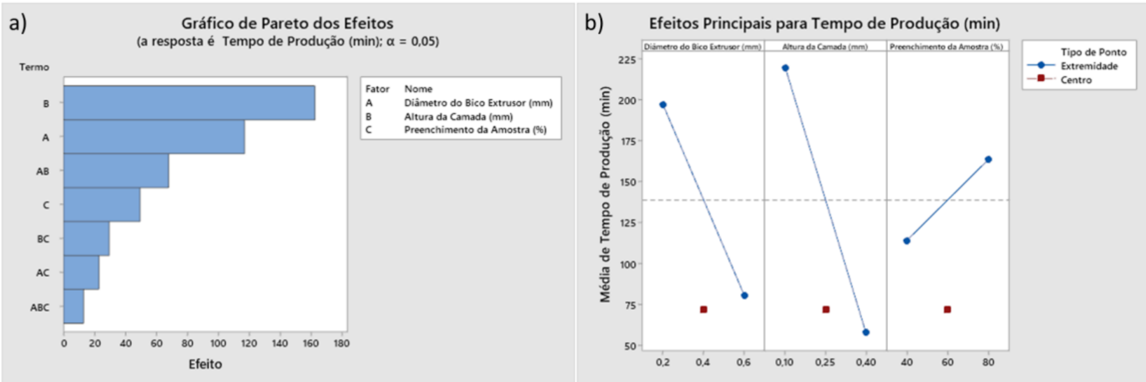
indication that the best model that will explain the phenomenon studied is not linear. Analyzing the influence of the factors addressed in production time, it is noted that the most expressive interaction between the factors is the diameter of the extruder (DBE) and layer height (AC). This interaction is followed by the relationship between AC and PA, DBE and PA, and there is interaction between all the factors analyzed.

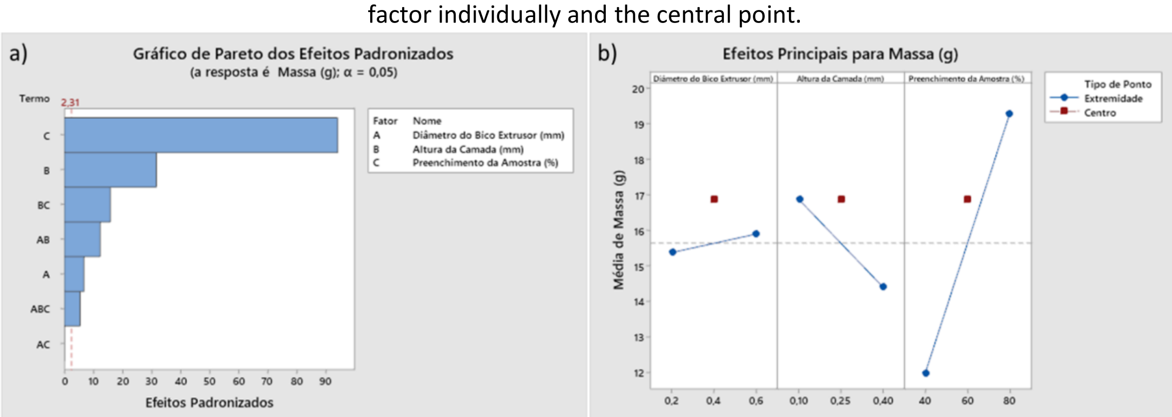
Figure 3. a) Relation between standardized effects and factors in the production time of each sample. b) Influence of each factor individually and the central point.



Note: a) The critical value line does not display the effect graph because the default value for effects is 0.

It can be noted in Figure 4 that the percentage of sample filling (PA) has an influence on the amount of mass used to manufacture orthodontic models. Reducing the values used for this parameter will reduce the amount of mass necessary to produce a sample. Meanwhile, the factors diameter of the extruder (DBE) and layer height (AC) have less influence when compared to the pre-filling. It is also observed that the central point offers an indication that the best model that will explain the phenomenon studied is not linear. It was also identified that the interaction between the AC and PA factors is more representative and is followed by the interaction between the DBE and AC. The interaction stands out, with lower intensity among the three factors analyzed.

Figure 4. a) Relation between standardized effects and factors in the mass of each sample. b) Influence of each factor individually and the central point.



The layer height factor (AC) has the greatest influence on the roughness of the incisor element (RC-I), Figure 5. By reducing the values used in this parameter, the average roughness of the incisor element is reduced. The sample filling (PA) and the diameter of the nozzle extruder (DBE) also offer significant influence on the roughness. Still, by increasing

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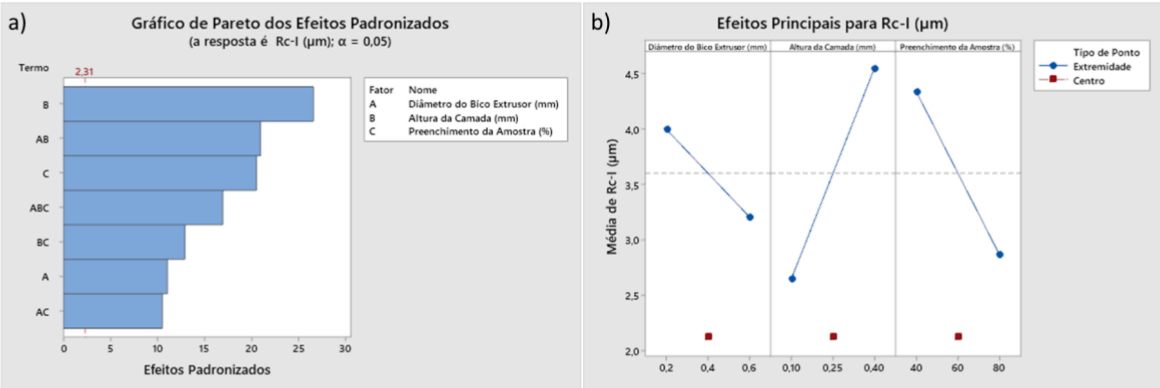
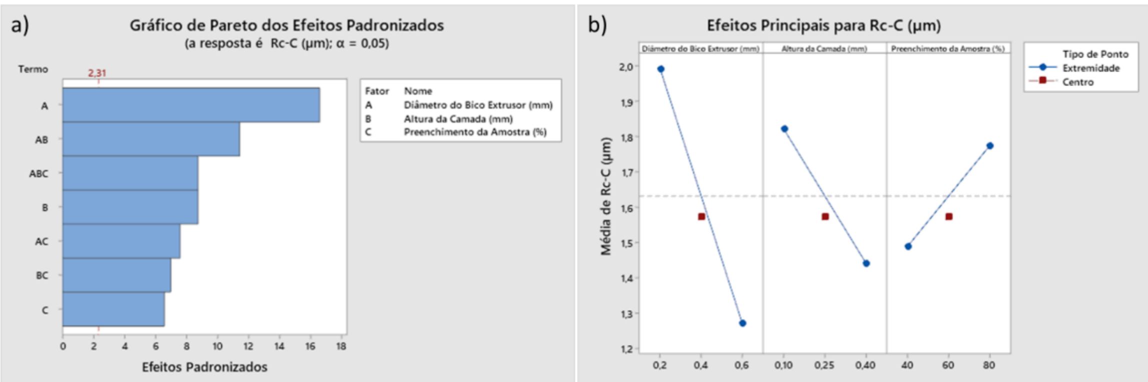
the values used in these parameters, there will be a reduction in the average roughness. As with the answers analyzed above (production time and mass), it is also highlighted that the central point offers an indication that the best model will explain the phenomenon studied in a non-linear manner. Also is identified by two-by-two interaction between the factors studied and the interaction between the three factors in the roughness of the incisive element.

Figure 5. a) Relation between standardized effects and factors in the roughness of the incisor element (Rc-I). b) Influence of each factor individually and the central point.



It is observed in Figure 6 that the diameter factor of the nozzle extruder (DBE) has the greatest influence on the average roughness of the canine element (Rc -C). By increasing the average diameter of the extruder, there is a reduction in the average roughness. It has now been identified that the factors of layer height (AC) and sample filling (PA) have a significant influence. The layer height has a similar effect to that found in the DBE factor and the filling factor is inversely proportional to the DBE. It is emphasized that the central point offers an indication that the best model that will explain the phenomenon studied is not linear. Analyzing the influence of the factors addressed in the average roughness of the canine element, all parameters analyzed through interaction for a studied response.

Figure 6. a) Relation between standardized effects and factors in the roughness of the canine element (Rc -C). b) Influence of each factor individually at the central point.



It can be observed in Figure 7 that the diameter factor of the nozzle extruder (DBE) has the greatest influence on the average roughness of the molar element (Rc -M). It was also that the layer height factor (AC) has an influence on the average roughness of the molar element. The factor such as percentage of sample preenchiment (PA) does not individually influence

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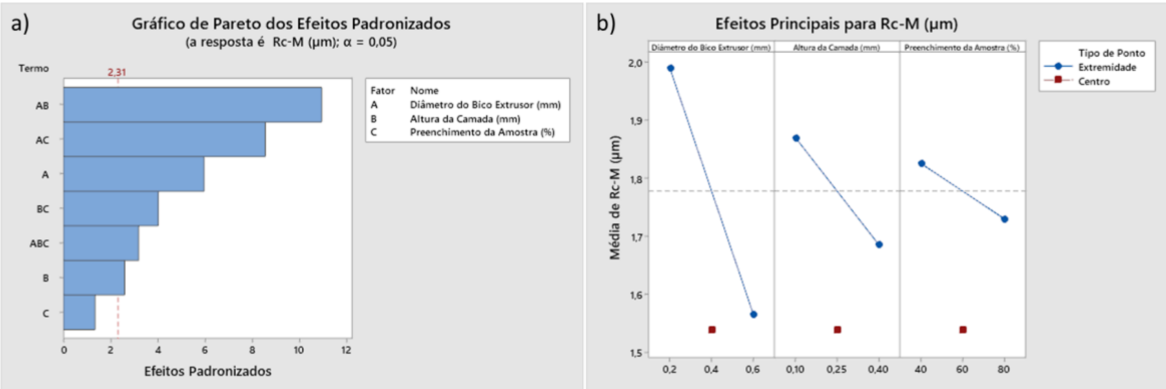
the average roughness. The increase in the parameters linked to both the diameter of the extruder (DBE) and the layer height (AC) was reduced to average roughness. It is also observed that the central point offers an indication that the best model that will explain the phenomenon studied is not linear. As well as identified for the roughness of the canine element, all the factors analyzed show a two-by-two interaction and the three factors together for the average roughness of the molar element (Rc -M).

Figure 7. a) Relation between standardized effects and factors in the roughness of the molar element (Rc -M). b) Influence of each factor individually and the central point.



FINAL CONSIDERATIONS

Considering the materials and methods used in the development of this work, the following final considerations can be obtained:

The production time of orthodontic models is influenced by factors such as the diameter of the extruder, the layer height, and the sample filling. There is still strong interaction among the three studied factors.

The three factors show individual influence over the mass of each orthodontic model. There is interaction between the factors layer height and sample filling; and among the factor's diameter of the extruders and layer height. It has been identified that the three factors show interaction in the quantity of mass of each orthodontic model.

The average roughness of orthodontic models is influenced by the factors: diameter of the extruder, layer height and sample filling.

Depending on the geometry of the region of the orthodontic model, the most influential factors alternate. For regions such as geometries similar to the incisive element, the most influential factor is layer height. For regions with geometries similar to the canine and molar elements, the most influential factor is the diameter of the extruder. For the regions analyzed there is still a strong influence between the three factors studied.

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