Transformation of orthodontics bracket geometry in metal injection molding process

S Supriadi[1], D Abdussalam[1], T Heriyanto[1], B Irawan[2], B Suharno[3]

[1] Department of Mechanical Engineering, Faculty of Engineering, University of Indonesia, UI Depok, Depok 16424, Indonesia
[2] Department of Dental Material, Faculty of Dentistry, University of Indonesia, Salemba Raya 4 St., Central Jakarta, 10430, Indonesia
[3] Department of Metallurgy and Materials Engineering, Faculty of Engineering, University of Indonesia, UI Depok, Depok 16424, Indonesia

sugeng@eng.ui.ac.id

Abstract. Orthodontic Bracket is a complex component; Therefore, it requires manufacturing process of a high accuracy like metal injection molding. Metal injection molding consists of three main steps. At first, the feedstock which is a mixture of steel powders and polymer is injected into a mold to form the desired design. Then the molded part is unbound to remove the polymer from the part, this process results in an absence of polymer that generates porosity. Furthermore, the unbound part is sintered to densify steel particles through capillarity force, this process is also the cause of part shrinkage that leads to a geometrical change. The bracket consists of three sections namely the geometrical functions that are affected by the sintering process, they are: wing, trunk, and base. The wing section works as a hook to hold the orthodontic ring, the trunk section supports all the bracket sections, while the base section provides surface contact with orthodontic adhesive. Each section of the bracket has its specific function namely to attach object with different geometries and to withstand a certain load. The functions will not work properly if during the sintering process the geometrical changes caused by shrinkage occurs. This paper presents transformation analysis of orthodontic bracket geometric transformation in the MIM process. In the case of wing geometry, the shrinkage of the outer part of the arch is greater than that of the inner part resulting the reduction on its slope from 35,01° to 32,11°. In the case of square geometry, the corners shrink greater than the edge side so that the square getting rounded, especially the bottom surface of the bracket that the radius of convexity reduced from 43.51 mm to 19.23 mm. The effects of shrinkage due to sintering have less impact on the trunk in the middle of the bracket that is equal to 7.23% on x-axis and 4.994% on y-axis while the wings section shrink by 10.98% on x-axis and -6.637% (elongated) on y-axis. In conclusion, the changes of size and shape are different from each section, depend on the section's geometry, the sintering tends to effect more on the outer side of geometry. The disproportion of shrinkage will result in overall shape change in the manufacturing outcome. On the wing of the bracket, there will be a thinning and a slope reducing that will increase the risk of fracture and can not refute the orthodontic rubber well. On the base, occurs the rounding that will reduce the surface contact on the adhesive that attaches the bracket to the teeth. To adapt to the geometrical change, the first design must be larger, and the part's faces must be designed to be more concave.

1. Introduction

The orthodontic bracket is used to align teeth and correct malocclusion of the teeth. It is transferring the force applied by orthodontic wire to the tooth [1]. The orthodontic bracket must be strong enough to apply the load while expected to be as small as possible to provide comfort.

There are several methods to fabricate an orthodontic bracket, such as machining, metal injection molding, investment casting [2]. The orthodontic bracket fabrication has to be economical for mass-production but also able to produce complex geometry with high dimensional tolerance. The machining process is good in producing high complexity shape but bad in mass-producing, while investment casting is the otherwise [3]. Therefore, metal injection molding is chosen to fabricate the orthodontic bracket.

Metal injection molding (MIM) is a process with several steps as shown in Figure 1. The first step is feedstock preparation, where the metal powder is mixed with the polymer. The second step is injecting the feedstock to the molding using a machine with a high temperature. The third step is unbinding, where the injected part is unbound to remove the polymer from the part, furthermore, the absence of polymer will result in porosity. The last step is sintering, where the unbound part is heated to fuse metal particle then make the unbound part denser.

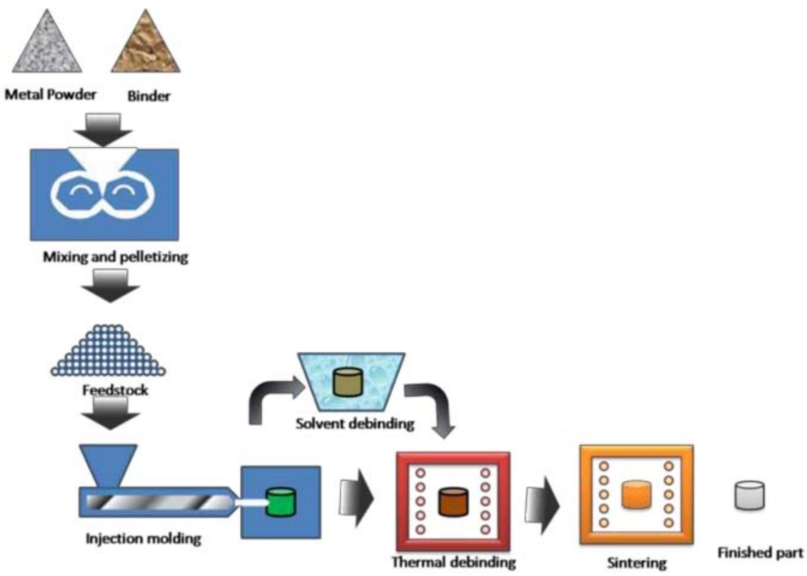

Figure 1. Illustration of metal injection molding process [4].

The long process of metal injection molding is the disadvantage of this manufacturing process. During the sintering, the part is not only shrinking, but also changing in geometry that is probably caused by ununiformly shrinkage all over the part [5].

This phenomenon makes it more complicated to design the mold. This paper focuses on formulating the geometrical transformation from which the result will be used to overcome the difference between the design and the end product.

2. Experimental method

This research was carried out in several steps. The first step was the machine and feedstock preparation. The type of feedstock used in this research is Stainless Steel 17-4PH which has a specific temperature of 200°C. The feedstock was injected using pneumatic injection machine with the force of 5.2 kN/m^2 and injecting-speed of 89 m/min, while the temperature of the barrel was 100 °C, the nozzle was 200 °C and mold was 50 °C. The second step was unbinding, this process consists of solvent and thermal unbinding. The solvent unbinding used agitation method with the temperature of 50 °C, the heating rate of 1 °C/min, and the holding time of 60-minute, during 90-minute duration. The thermal unbinding use the temperature of 510 °C, the heating rate of 1 °C/min, and the holding time of 60-minutes. The third step was sintering, this process occurred under vacuum atmosphere with the temperature of 1360 °C, and the holding time of 1.5 hours [6]. The last step was comparing and analyzing the geometrical differences between the design and the end product.

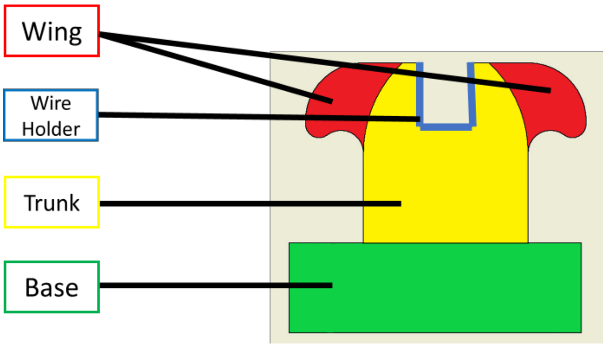

Figure 2. The four sections of orthodontic bracket from front view.

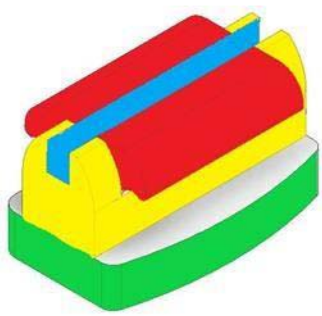

Figure 3. The four sections of orthodontic bracket from isometric view.

For analytical purpose, the bracket was divided into 4 sections based on their geometries and position as shown in Figure 2 and Figure 3. Each of the sections have their specific functions and withstood loads, therefore, they used different calculations to determine the shrinkage occurred and its criticality to the functions. The shrinkage was calculated using a formula in equation (1).

$$Shrinkage = 1 + \frac{size\ after\ sintering}{size\ before\ sintering} [\%] \tag{1}$$

The wings section as illustrated in Figure 2 and Figure 3 is thick hooks extruded along the bracket's length, both on the right and the left side with bilateral symmetry. This section works as a hook to hold the orthodontic ring. The lower arc of the wing (as illustrated in Figure 4) is important to hold the rubber on, since the rubber won't hold safely if the curve is too flat. The angle of the hook (as illustrated in Figure 5) is also important to keep the rubber held on. Therefore, the measurement need to be done to prevent unexpected size changes which reduces the wing function to hold the rubber. The angle of hook is measured in degree relative to the trunk.

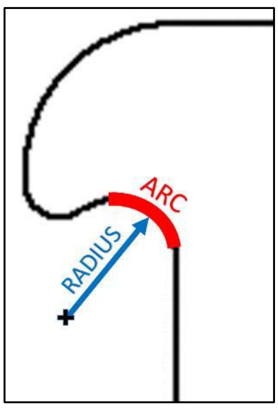

Figure 4. The lower arc of the wing (red) and its radius (blue) measurement.

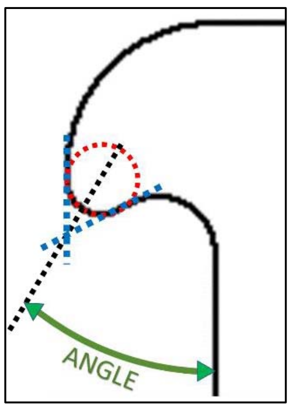

Figure 5. The hook's angle measurement.

The base section as illustrated in Figure 2 and Figure 3 works to provide surface contact to the tooth. The excessive surface rounding on the bottom of the base that can be caused by manufacturing process such as sintering, will reduce the surface contact with orthodontic adhesive and increase the risk of the bracket to detached from the tooth. Therefore, measurement is important to find out how much of the surface rounding has occurred.

As shown in Figure 6, the surface rounding was determined by the radius of roundness that appeared as an arc line on 2-dimensional view. The corner roundness was also measured to determine sintering reactions that occurred in different shapes as shown in Figure 6.

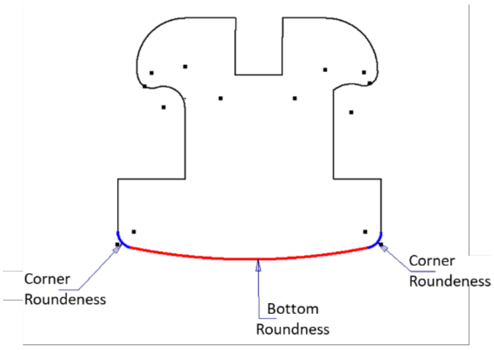

Figure 6. Bracket's base measurement method.

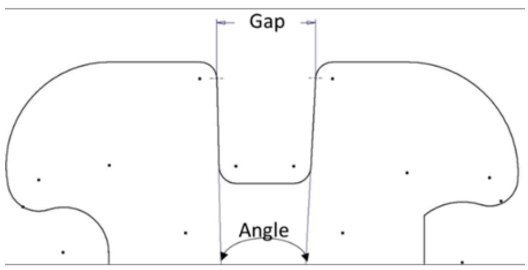

Figure 7. Wire slot measurement method.

The wire slot section as shown in Figure 2 and Figure 3 as is a u-shape cavity that receives the torsional force from the orthodontic wire.

The wire slot was designed to be bigger than the wire to give a space that prevents an unexpected friction with the wire. Therefore, the measurements need to be done on the parameters that indicate a narrowing of the slot, those parameters are the gap and the angle as illustrated in Figure 7.

3. Result and discussion

The results of the measurements are geometry's comparations of each section before and after sintering process. The differences in shrinkage ratio are also used to find the correlation between shape and shrinkage. Furthermore, the results are related with heat distribution on the sintering furnace.

3.1. Overall body shrinkage

To analyze the shrinkage that has occurred in different dimensions, the measurement is conducted by comparing the 5 components of measurement that are shown in Figure 8. From the data provided in Table 1, the most shrunk dimension is the length of the bracket that shrinks 10.95% along the z-axis while the least shrunk is the height of the base that shrinks only 0.85% along the y-axis. Based on the measured data, the longer the geometry was likely to shrink greater than the shorter geometry. Based on comparison between 3-axis dimension, the dimensions along the z-axis are shrinking the most while the dimensions along the y-axis are shrinking the least.

The reliability of transformation of before and after sintering was checked by *Pearson product-moment* correlation. The correlation coefficient reflects the relations of shrinkage and sintering,

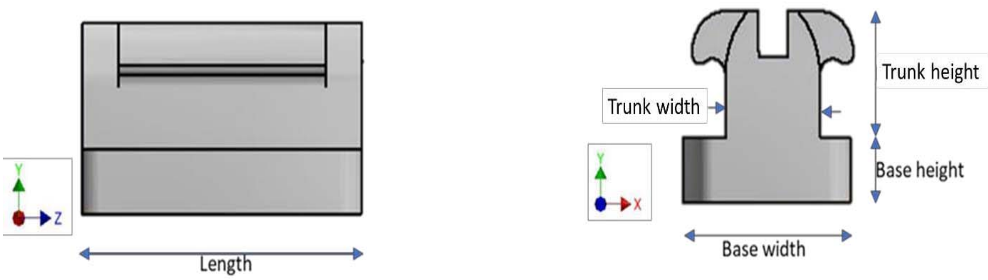

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Figure 8. overall body measurement.

since the shrinkage would have nothing to do with the sintering if the correlation has not satisfy the requirement. The correlation check concludes that the sintering effects all measured dimension to be shrunk except a shrinkage in trunk height. The shrinkage of trunk height has a p-value of 0.845917 that exceeds the significant level of 0.10, therefore the geometrical transformation is not related to the sintering.

Table 1. Measuring results from the Figure 8.

	Size (mm)			
Dimension	Design	Before Sintering	After Sinterin	Shrinkage due to
Length	5.400	5.947	5.295	10.95%
Trunk Width	1.825	1.994	1.850	7.24%
Base Width	3.240	3.350	3.179	5.11%
Trunk Height	2.000	2.086	1.982	4.99%
Base Height	1.000	1.175	1.165	0.85%

3.2. Bracket base geometric transformation

The corner rounding, and bottom rounding as illustrated in Figure 9 and Figure 10, are the indicators of the base geometrical transformation. The results of the measurement are shown in Figure 11. After the sintering, the bottom surface of the bracket seems to be more rounded than before.

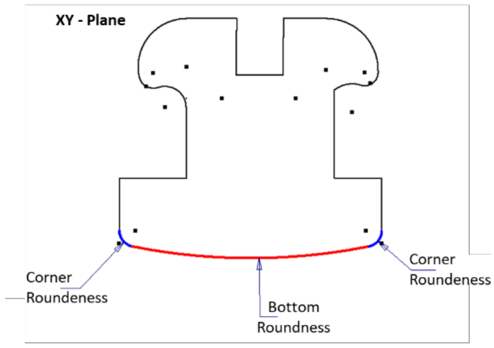

Figure 9. Definition of bottom roundness and corner roundness on xy-plane.

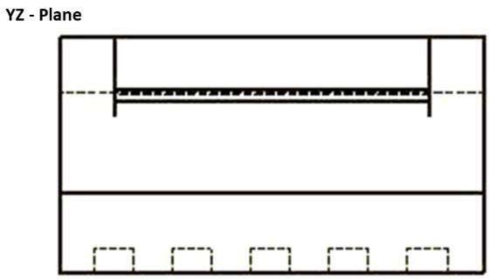

Figure 10. Definition of bottom roundness and corner roundness on yz-plane.

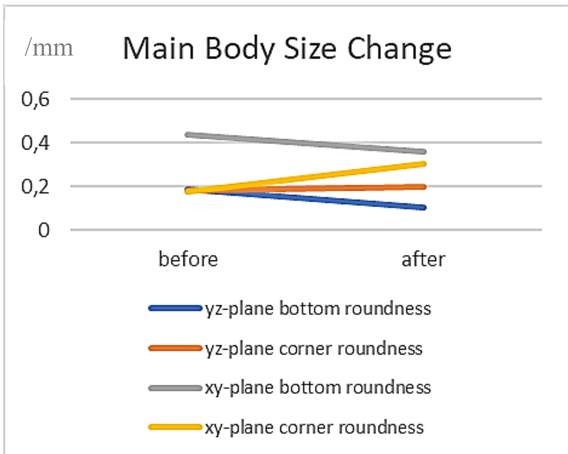

Figure 11. Roundness change in radius.

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From the data obtained in Figure 11, the corners roundness radiuses are reduced while the bottom roundness radius is increased. This indicates that the shrinking move along the edge toward the center of geometry which resulting in the rounding on the base surface as the illustration in Figure 12.

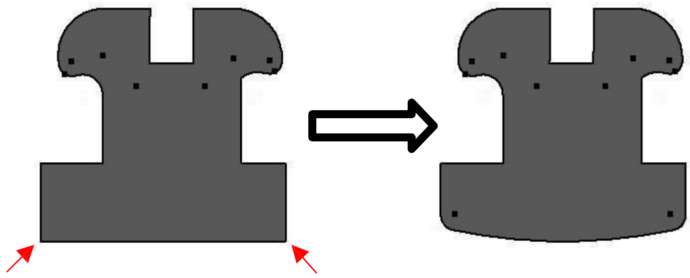

Figure 12. the red arrows represent the shrinking direction on the edge that resulting in the geometric on the right side.

3.3. Wing geometric transformation

The wings width is shrinking while the heights contracted. The wing shrinks along the x-axis for 6.92% and stretches along the y-axis for -6.11%. The shrinkage and contraction are not uniform on all the section of the wing geometry, so the leaning angle measurement is conducted to understanding the pattern. The details are presented in Table 2.

Table 2. Wing geometry shrinkage.

	Shringkage			
Dimension	Left Wing	Right Wing	Average	Percentage
X-Axis	0.034 mm	0.05 mm	0.04 mm	6.92%
Y-Axis	-0.022 mm	-0.07 mm	-0.05 mm	-6.11% (stretch)
Cross-section area	0.01 mm^2	0.019 mm^2	0.014 mm^2	3.4%

During the sintering, the hook slop moves leaning down. The angel measured by inspecting the direction of the arc in the end of the hook to the y-axis.

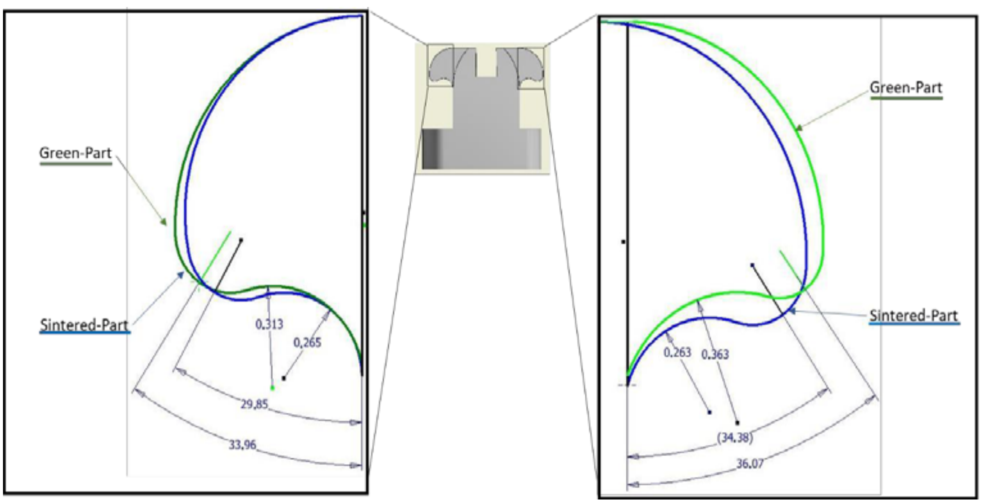

Figure 13. The angle of leaning difference before (green) and after the sintering (blue).

Based on Figure 13, the angle of the hook is reduced indicate that there is a partial rotation occuring on the wings. The average of the anglular decreased is 3°, but there is uncertainty if the leaning angle is a linear transformation since the geometry is complex. The radius of the lower arc of the wing is decreasing from 0.50 mm to 0.45 mm which means that the orthodontic rubber will safely hold even after the part was sintered.

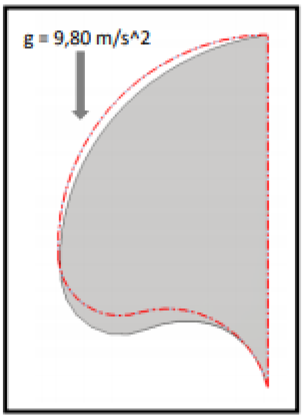

Figure 14. Gravitational influence simulation on the green-part with the gravitation of 9.8m/s^2 and fix constraint to the right side. The red dashed line represents the geometry before gravitation influence and the grey solid after the influence.

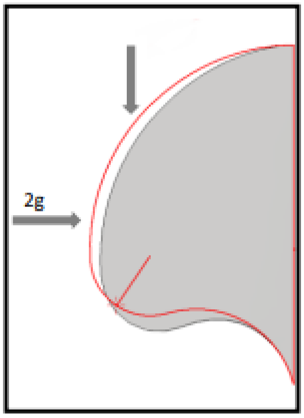

Figure 15. Gravitational influence and additional force to simulate a shrinkage movement. The red line represents the pre-gravitational influence geometry and the grey solid line represents the post-gravity influence geometry.

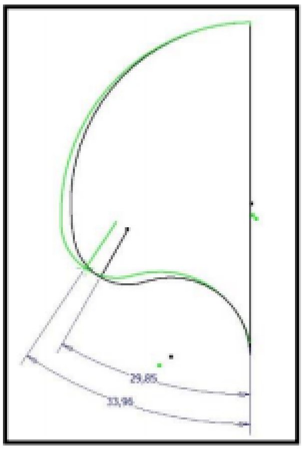

Figure 16. Left-wing geometric transformation before and after sintering.

The furnace heats the sample through radiation during the sintering process. The heat distribution imaging as shown in Figure 17, occurs during unsteady state at the uncertain time. Since the purpose only to estimate which part experience the geometrical transformation earlier, the exact time is considered to be unnecessary. Overheating will turn the phase of the metal particles from solid-state to

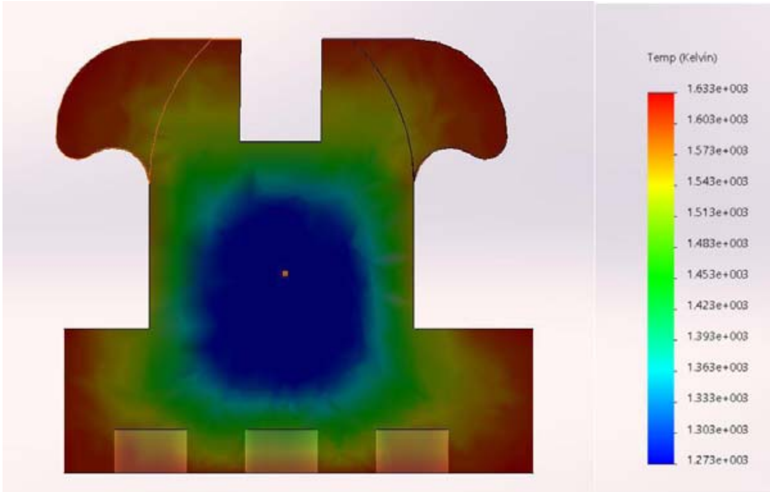

Figure 17. Heat distribution on the bracket cross-section during the sintering process. The simulation is conducted using *Solidworks* thermal analysis.

liquid-phase. The liquid-phase causes the bond between particles to loosen and easier to attract by the gravitational force [7]. The simulation is conducted to compare the geometrical change of the wing caused by sintering process with the geometry change caused by the influence of gravitation. This simulation uses CAD software for measuring bending disposition. By adjusting the parameter, the software will be able to simulate the gravitational influence accurately. Based on the heat distribution simulation on Figure 17, the inner side of the wing attached to the trunk receives less heat. Therefore, the inner side is assumed to not experience any geometrical changing and considered to be a fixed constraint. The force applied on the bending is equivalent to the wing mass that is distributed in all parts of the wing. The result of this simulation is shown in Figure 14. Based on the comparison of Figure 14 and Figure 16, the simulation has not been similar enough to the result of sintering. This means that there is another significant factor that must be calculated.

In the second simulation, the axial force along x-axis toward the trunk is added to simulate the shrinking force. The magnitude is based on the uniform force on the wing plane with weight value of 2 times gravitation. The particles densifying also depends on the heat distribution, therefore the shrinkage assumed to occur less on the inner (right) side of the wing. The result of the second simulation is shown in Figure 15.

As shown above, the second simulation result in Figure 15 is closer to the geometrical change of the sintering process in Figure 16. Based on the comparison, the research concludes that in this sintering process, both shrinkage and gravitation influence is significant to a hook geometric transformation of the wing section.

3.4. Wire slot geometric transformation
The gap of the upper cavity is narrowing by 0.02 mm and the angle is increased by 3° as shown in Figure 18. The u-shape cavity is opening but upper and lower gap is narrowing, since the angle is increasing, the lower gap is narrowing greater than the upper gap. However, the variables between the gap length and angle of before and after sintering are not correlated since the p-value of the gap (0.6855) and the angle (0.4734) is exceed the significant level (0.10).

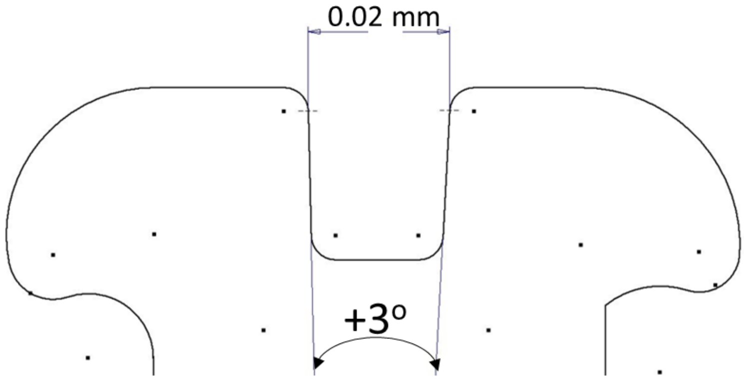

Figure 18. Wire slot measurement method.

4. Conclusion

During the sintering process, the geometries of the orthodontic bracket are transforming. The transformations are different in each section of the bracket, depend on the geometries. The longer geometry tends to shrink more than the shorter geometry based on the shrinking percentage. The edge and the corner side of the geometry tend to shrink more than the face side of the geometry, this phenomenon is related to the heat exposure direction. The gravitational attraction influences the geometric transformation, especially on the geometry with the less support. The wing geometry is leaning down, the base surface geometry is rounding. Since there is a shrinkage from the molded part into the sintered part, the design of the mold must be larger, with the part's face must be more concave to adapt the geometrical change caused by sintering that resulting the desired dimension product. Therefore, for the base section of the mold, the design of bottom surface should be concave with the radius of 43.51 mm along the width and 88.86 mm along the length. For the wing section of the mold, the width and the height respectively are set to be 7.43% and 6.51% bigger then the first design. For the overall body, the length, trunk width, base width, trunk height, base height, respectively are set to be 12.29%, 7.80%, 5.38%, 4.37%, 0.86% bigger than the first design.

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