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RESEARCH ARTICLE

Effect of Antagonist Material Geometry on Titanium Biomaterials Two-Body Wear Behavior: Finite Element Analysis Study

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ABSTRACT

In recent years, the Finite Element Analysis method has been preferred due to its many advantages such as mathematical modeling, short time, and more experimental parameters. This study aimed at finite element analysis of two body wear behavior titanium-based biomaterial under chewing test procedures. Pure titanium test material was subjected to a 6 mm cylinder and 6 mm length square geometry antagonist abrasive material, 50 N bite force, 2 Hz chewing frequency, 0.7 mm lower jaw movement, finite element analysis chewing process. As a result of this study, force distributions occurred in the wear area of the test material in the chewing test mechanisms performed with both antagonist abrasive materials. However, the chewing bite load distribution from the cylindrical antagonist material showed a more homogeneous behavior compared to the square antagonist material. Additionally, stress concentrations were observed in certain regions of the square antagonist abrasive material. This may cause the test material to suffer from excessive wear and volume loss and damage may occur due to different deformation mechanisms.

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1. Introduction

Titanium and titanium alloys are preferred as biomaterials due to their mechanical, chemical, and aesthetic behaviors. It has been reported in the literature that titanium alloys can be preferred in the treatment process due to their superior behavior such as high strength-to-weight ratio, good fatigue resistance, relatively low Young's modulus, good biocompatibility, and high corrosion resistance [1]. However, titanium and titanium alloys placed inside the body as biomaterials can be exposed to various damage mechanisms. Wear mechanisms, which are the basis of these damage mechanisms, can significantly affect the mechanical behavior of titanium and titanium alloys. It has been reported in the literature that the wear behavior of titanium and titanium alloys does not show the expected performance [2]. Various complex wear mechanisms can occur in different parts of the human body. These wear mechanisms can be grouped as two-body, three-body, fatigue wear, and corrosive wear. Biomaterials placed in the human mouth are inevitably exposed to various fatigue, corrosion, and wear mechanisms during the chewing movement. To provide

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long-term satisfactory treatment, it is important to know the wear and fatigue behavior of biomaterials placed in the human mouth in various periods. Because experiments performed on living tissue (in vivo) take a long time, are expensive, and ethical problems are encountered, researchers have turned to in vitro test methods. With laboratory (in vitro) test methods, the wear and fatigue behavior of a biomaterial that can remain on living tissue for years can be evaluated in very short periods (such as a 10-20-day test period). Another great advantage of this method is that the mechanical and chemical behavior of biomaterials developed in recent years for the human body can be determined in very short periods without using them on living tissue. Another analysis is the 3D computer-aided finite element method, in which experimental study parameters can be modeled through the chewing test process. With the finite element analysis method, the effect of experimental parameters on the test material is analyzed in real-time. In the literature, researchers have analyzed the effect of chewing movement on the test material through various methods [3, 4]. However, the human body has a continuous and very complex structure. It is known that biomaterials placed in the human body can be subject to various wear and fatigue mechanisms in a continuous and complex structure. It has been reported that four main wear mechanisms occur during chewing motion [5].

It is possible to define these wear mechanisms as direct contact wear (two-body), the presence of a third corrosive environment (three-body), subsurface cracks caused by repetitive loading in the material (fatigue wear), and mechanisms caused by the corrosion environment (corrosion wear). In the direct contact wear mechanism (two-body wear), it occurs with the direct contact of the counter material and the base material, and with this contact, force is transferred at various amplitudes between the two materials. In the abrasive environment (three-body wear) wear mechanism, third abrasive particles (such as food particles during chewing) are included between the abrasive material and the counter material, and direct contact is prevented. It has been reported in the literature that direct contact wear and abrasive environment wear mechanisms are the basic wear mechanisms that occur during chewing movement [6–9].

2. Material and Methods

In this study, a finite element chewing test simulation of titanium bio-material was carried out using the ANSYS 19 workbench academic version program. For this reason, the mesh amount is set to a maximum of 30.000 which this ratio is in a range of values sufficient for the analysis performed finite element chewing test analyses. The material was chosen as a titanium alloy from the general material library of the ANSYS program. The mechanical properties of pure titanium, test samples, mesh test samples, and counter-abrasive materials tested in this study are shown in Figure 1.

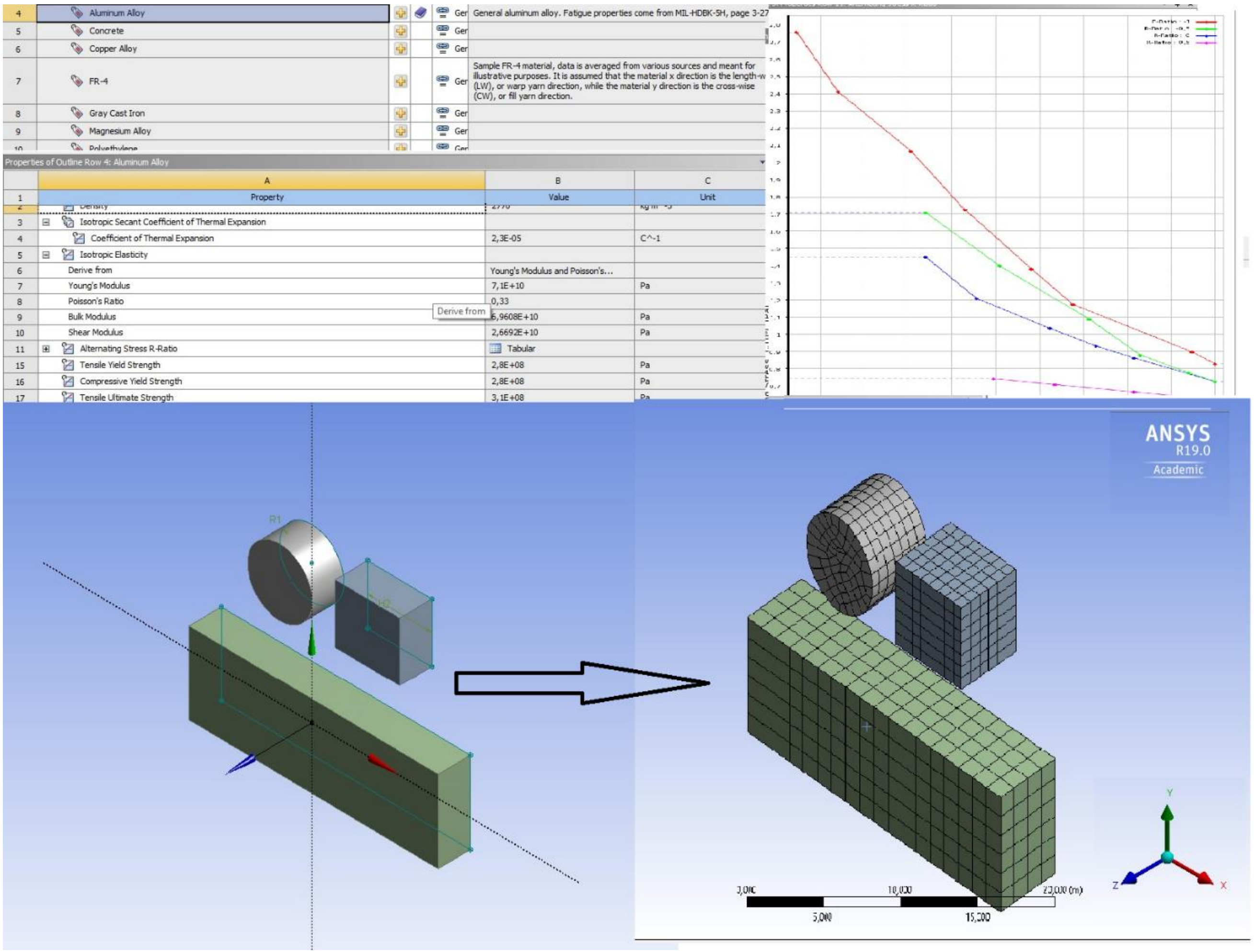


Figure 1 The mechanical properties of pure titanium, test samples, mesh test samples, and antagonist abrasive materials

Pure titanium test material was subjected to a 6 mm cylinder and 6 mm length square geometry antagonist abrasive material, 50 N bite force, 2 Hz chewing frequency, 0.7 mm lower jaw movement, finite element analysis chewing process. Antagonist-abrasive materials with both geometries were simultaneously subjected to finite element chewing test simulation. Bite force distributions were analyzed during the chewing tests in the loading and unloading time domain. Bite force loading of 50 N and a sliding motion of 0.7 mm through finite element chewing analysis simulation in the modeling, a force of 50 N was applied perpendicular to the test sample (in the - z-direction). For the test specimen to move in the horizontal axis, the rotary motion of the test specimen was provided at a frequency of 2 Hz by using a wear coefficient of 2 N (in the x direction). The wear coefficient varies according to the material's surface behavior. However, in this study, pure titanium material was considered to be under optimum conditions. In this study, the wear mechanism is designed as a dynamic process. In this process, many parameters can affect the wear mechanism. However, for the experimental results to be interpreted as stable, the parameters other than the active parameter were considered to remain constant. The wear mechanism can be formulated as follows;

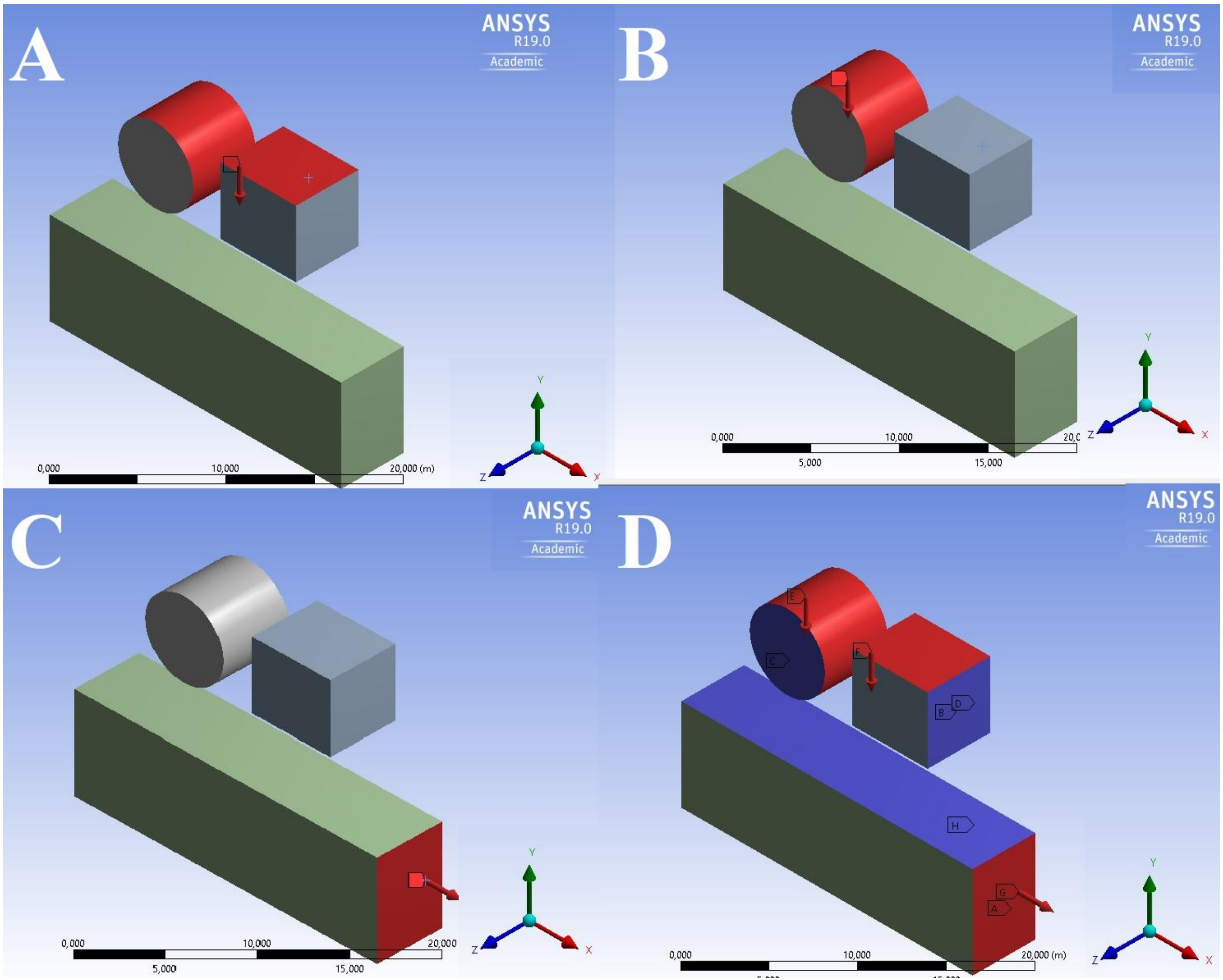
$$f(x) = \frac{\text{dH}}{\text{ds}} \quad (1)$$

In this formula, “s” = sliding distance in m and “h” = wear depth in m, “f(x)” represents the load parameters. As a result of this study, the standardized pressure "p", which corresponds to the biting force, and the standardized speed "v" as an element give the shapes of the wear regime and the dimensionless wear rate "Q" and are characterized:

$$Q = \frac{V}{As}, p = \frac{Fn}{AH}, \quad (2)$$

where “V” is the volumetric wear rate in m^3, “A” is Visible contact area in square meters FN = normal load in Newton’s, H=hardness in Pa, v = shear speed in m/s,

Figure 2 shows the process steps of the chewing cycle test simulation movement. (A: Application of the bite force to the square counter material, B: Application of the bite force to the circular counter material, C: 0.7 mm lateral movement of the base test material at the moment of the bite force, and D: The effect of the test parameters on the materials at the moment of 1 cycle chewing movement



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3. Results

The chewing simulation movement consists of three stages. Step 1 can be summarized as the upper jaw coming into contact with the lower jaw (bite force process), step 2 being the lateral movement of the lower jaw (grinding process), and the last step being the end of the contact of the upper jaw with the lower jaw. In this study, the load distribution occurring in the abrasive material against the flow during the contact of the upper jaw with the lower jaw in the chewing test simulation is shown in Figure 3.A. Afterward, the grinding process in the chewing simulation is completed with the lateral movement of the lower jaw, shown in Figure 3.B. Finally, the chewing cycle is completed by separating the upper jaw from the lower jaw, as shown in Figure 3.C. The summary of the chewing simulation in the laboratory environment and on living tissue is shown in Figure 3.D.

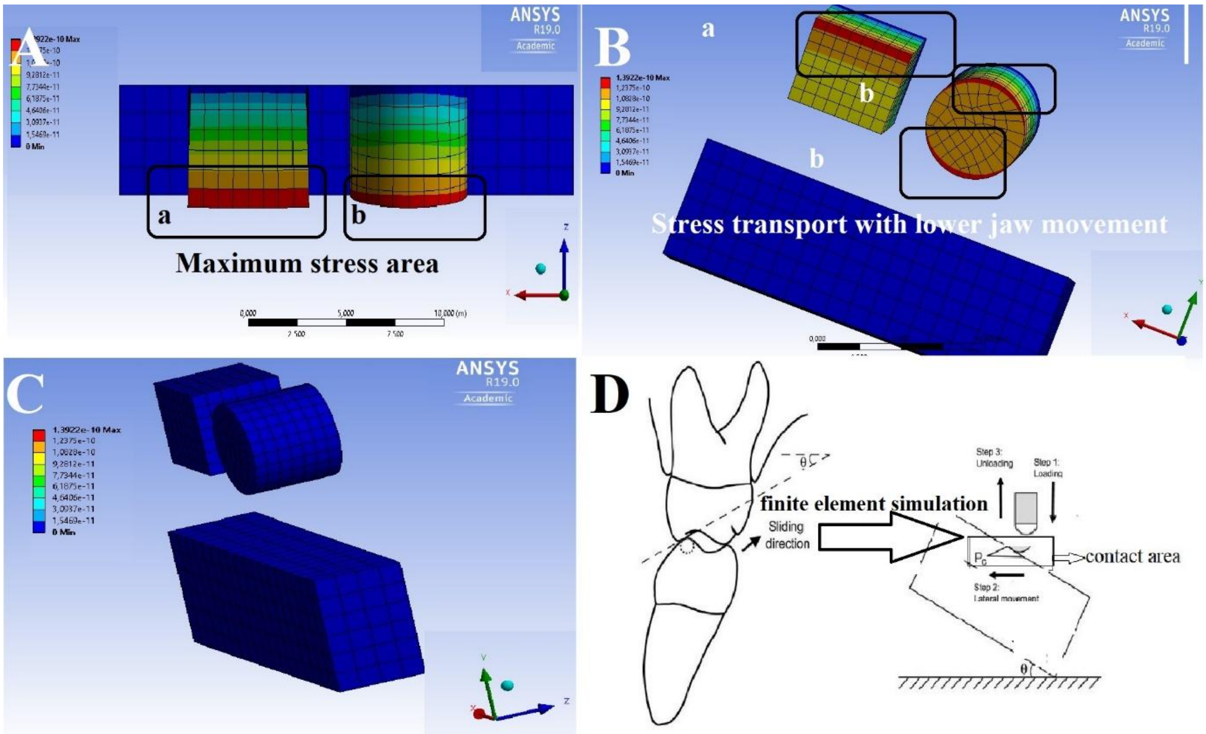

Figure 3Chewing bite stress changes in the antagonist abrasive material during chewing movement (A: Maximum stress area both in antagonist material geometry, B: Stress transport with lower jaw movement, C: Chewing cycle is completed by separating the upper jaw from the lower jaw and D: The summary of the chewing simulation in the laboratory environment and on living tissue

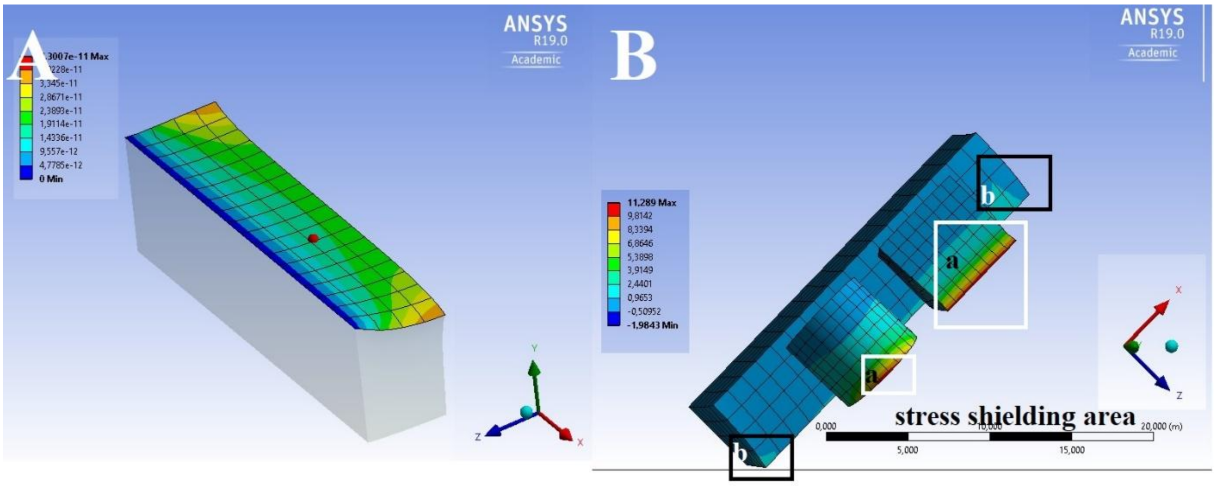

Figure 4 Two-body wear and stress shielding behaviors occurring on the test material and counter material during chewing(A: The two-body wear area on the test material that occurred during the chewing test simulation and B: The load distribution effect of the wear contact area on the antagonist abrasive material)

The two-body wear area on the test material that occurred during the chewing test simulation is shown in Figure 4.A. The load distribution effect of the wear contact area on the antagonist abrasive material is shown in Figure 4B.. It can be seen that the antagonist abrasive material exhibits different two-body wear behavior in different geometries (Figure 4.B(a)). In addition, the stress shielding on the antagonist material surface contributed to the excessive chewing bite force on the wear surface of the test material (Figure 4.B(b)).

4. Discussion

In this study, the contact of counter-abrasive materials with cylindrical and square geometry with the test material during the bite force lower jaw movement was analyzed through finite element analysis chewing simulation. Both antagonist abrasive materials caused various deformation mechanisms on the test material wear surface. However, chewing bite load distributions and stress shielding on the antagonist abrasive material can provide information about the deformation mechanisms occurring on the wear surface. Because the chewing bite load distribution on the antagonist abrasive material was transferred to the test material during contact, thus occurred the two-body wear area. If the distribution of the chewing bite force on the antagonist abrasive material surface is homogeneous, the wear area of the test material is also expected to be homogeneous. It is a known fact that excessive loads in the wear mechanism can cause plastic deformations in the test material. The wear resistance of biomaterials in chewing tests carried out in in vitro laboratory environments can vary according to many parameters such as ambient temperature, axial structure of the applied bite force, chewing frequency, *etc.* The fact that wear occurs in the contact area between at least two surfaces reveals the importance of antagonist abrasive material behavior. It is estimated that the geometry of the antagonist abrasive material, as well as its mechanical and chemical behavior, may affect the chewing wear mechanism. Therefore, in this study, the effect of cylindrical and spherical geometry of titanium dioxide material on the wear resistance of titanium pure material was analyzed through chewing test procedures.

It has been reported in the literature that different wear mechanisms occur depending on the exposure of teeth and dental restorative materials to various physical and chemical environments during the chewing process and the contact behavior of the antagonist material with the test material [10]. Differences in mechanical properties between antagonists can lead to excessive local material losses, resulting in decreased chewing function and fatigue of the chewing muscles. Therefore, antagonist abrasive materials acting on restorative materials should behave as similar to natural teeth as possible [11]. It is a fact that in chewing tests, not only the material structure but also the experimental conditions have an impact on the mechanical behavior of the material. When picture 3 is examined in this study, it is seen that the maximum stress area of the square abrasive material is larger compared to the circular counter material. From an engineering perspective, this result can be explained by the action-reaction principle in a chewing dynamic structure. In other words, the bite force effect stress shielding on the antagonist material was transferred from the base material back to the antagonist material. In modeling studies previously carried out on square and circular test samples in the literature, it was reported that stress accumulation was higher in square test samples [4]. These results show the effect of the geometry of the test materials and antagonist materials selected in the laboratory environment on the wear mechanism. When Figure 4 is examined, it is seen that a wear area occurs in the test material. This wear area has a hemisphere-like structure with the effect of the lateral movement of the lower jaw during the chewing test. The mechanical and chemical behaviors of the antagonist abrasive material and the test material during their contact affected the structure of the wear area. For these reasons, the superior capabilities of the testing device in chewing simulation tests carried out in the laboratory environment will increase the validity of the test results.

It has been reported in the literature that many chewing simulator devices simulate intraoral tribology by creating direct-contact wear and abrasive environment wear mechanisms [6, 8, 9, 12, 13]. The parameters applied in chewing simulators have a significant impact on the wear behavior of the composite and metal-based biomaterials. Therefore, for the validity of laboratory experiments, the parameters applied by chewing simulator devices must be similar to the parameters occurring in intraoral tribology. In the literature, it has been reported that bite force in intraoral tribology varies between 20 N and 120 N [14] The amount of 50 N bite force (vertical loading) selected within the scope of this study was considered an average stress during chewing for finite element analysis study. In many in vitro laboratory studies in the literature, the average bite force was selected as approximately 50 N [6–9]. Chewing bite force laboratory testing experiments have generally been performed using dead weight. For example, 5 kg dead weight corresponds to approximately 50N chewing bite force. The biggest advantage of this system is that the force shows similar behavior throughout the experiment. In this study, choosing the preferred bite force under laboratory environmental conditions contributed to the adaptation of the experimental results to the in vitro experimental results.The mechanical effect of the wear mechanism that occurs during chewing on teeth and dental materials is directly related to the test material geometry. Therefore, the structure of the antagonist abrasive material geometry was effectively selected within the determined chewing cycle test parameters. These mechanical deformation mechanisms can affect the optimum lifespan of teeth and dental materials placed in the human mouth. Because chewing bite force distributions occurred in the wear area of the test material in the chewing test mechanisms performed with both antagonist abrasive materials. However, the chewing bite load distribution from the cylindrical antagonist material showed a more homogeneous behavior compared to the square antagonist material. Additionally, stress concentrations were observed in certain regions of the square antagonist abrasive material.

In the literature, laboratory studies have reported that the number of chewing movements in intraoral tribology varies between 50,000 and 1,200,000 and that a person makes an average of 300 to 700 chewing movements per day [6]. In laboratory chewing tests, the geometry, size, and mechanical properties of the antagonist abrasive material have a great impact on the wear behavior of the composite and metal-based biomaterials. Therefore, in this study, the use of circular Al_2O_3 balls for reference antagonist material with a diameter of 6 mm was preferred for finite element analysis chewing test simulation. It has been reported in the literature that circular bead balls with a diameter of 6 mm simulate abrasive counter material during chewing movement on living tissue [6, 15]. In the literature, it has been reported that the wear mechanism in composite restorative materials in intraoral tribology occurs in two stages [5] Firstly, with the wear of the organic matrix structure in the composite material, inorganic particles move away from the monomer structure and a rough structure occurs on the wear surface [16]. In future studies, modeling of composite restorative materials with the finite element analysis chewing test method will contribute to the stability of in vitro laboratory test results.

5. Conclusion

Wear modeling the effect of chewing movement on biomaterial in a time band using by finite element method that makes a great contribution to the interpretation of test results. In this way, it makes it easier for researchers to develop materials and determine the optimum working life of biomaterials. In addition, this test method allows the results obtained in laboratory test methods to be interpreted mathematically and thus can explain the cause-effect relationship between test parameters. The structure of the counter-abrasive material geometry was effectively selected within the determined chewing cycle test parameters. Chewing bite force distributions occurred in the wear area of the test material in the chewing test mechanisms performed with both antagonist abrasive materials. However, the chewing bite load distribution from the cylindrical antagonist material showed a more homogeneous behavior compared to the square antagonist material. Additionally, stress concentrations were observed in certain regions of the square antagonist abrasive material. This may cause the test material to suffer from excessive wear and volume loss and damage may occur due to different deformation mechanisms. As a result of the study, it is thought that the load distributions obtained on the antagonist material will contribute to the interpretation of the experimental study results. Therefore, in future studies, testing similar wear mechanisms experimentally and with finite elements will contribute to more stable results.

Conflict of Interest

Author declares that they do not have any conflict of interest.

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