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Investigation of Temperature and Stress Distributions in a Dental Implant Prosthesis

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Abstract

Titanium and its alloys are widely used in various implant applications due to their biocompatibility and the ability to modify their alloy compositions. Because of its minimal impact on the human body and its resistance to chemical reactions, titanium has become popular in the field of dentistry in recent years and is considered a safe option for implant applications. Artificial dental crowns and dental root implant prostheses are typically produced using titanium alloys (Ti-6Al-4V). In this study, the FE package software ANSYS was used to investigate temperature and stress distribution in a dental implant prosthesis. 3D model was created and subjected to two different input conditions: two different temperatures (45° C and 10° C) under the 100 N compressive load and a fluid (beverage + air) flow rate of 1 m/s. The highest temperature was considered as food/beverage taken from a stove, while the lowest temperature was considered as beverage temperature taken out of the refrigerator. Based on the results of the thermal, von Mises stress, and total deformation analyses, it was determined that the implant prosthesis did not conduct heat well to the tooth root and had good compressive strength (48 MPa) under the load, which was better than its yield strength. Furthermore, it was found that a significant portion of the applied load was borne by the artificial dental crown. The aim of this study is to investigate the thermal and mechanical properties of the Ti-6Al-4V alloy, the behavior that is occur when it is exposed to temperature and compression stress. In this context, it is aimed to determine the incompatibilities that may occur at the bone-implant interface and to emphasize that mechanical compatibility is an important issue besides biocompatibility.

Key Words

"Dental prosthesis, Finite Element Analysis, Thermal and Stress Analysis, Ti-6Al-4V, Single Tooth"

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1. Introduction

1.1 Anatomy of the tooth

The tooth is each of the small bone-like and hard formations in the mouth, which is the beginning of the digestive system, one end of which is embedded in the bones of the upper and lower jaws and the other end is free and is the organ whose main function is to provide mechanical digestion of foods. As it can be seen in Fig. 1, the tooth; It consists of enamel, dentin, cementum, and tooth pulp. Enamel is the hardest substance in the body. It surrounds the tooth as an outermost protective layer. It is not sensitive because it does not contain nerve cells. 97% of its structure is made of consists of calcium salts. Dentin is the layer below the enamel. It makes up 75% of an adult human tooth. Although it has the same density as bone, it is sensitive to heat and touch. When necessary, they can regenerate dentin tissue with the repair cells they contain. Cementum is a bony layer that covers the root and is very thin. It allows the tooth root to attach to the jawbone. 65% is inorganic matter. Pulp (Tooth Core) is the name given to the middle part of the tooth and the soft tissue found here. It continues to the tip of the root. There are blood vessels in this part, and thanks to these vessels, the tooth is protected from infection and always remains active.

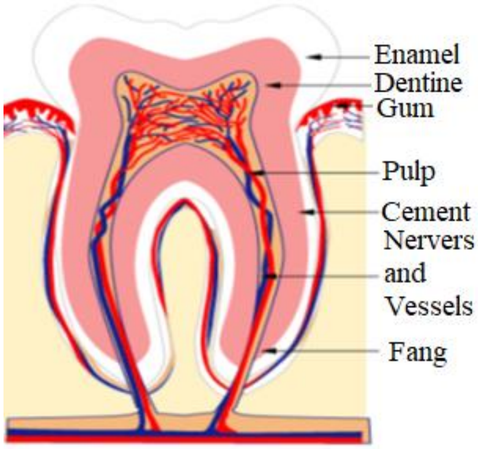

Fig. 1. The structure of the tooth (Dentanorm, 2018)

The tasks of the teeth seen in Fig. 2 are briefly as follows: The front teeth in the lower and upper jaw are called “incisors”. The canines, which are also called "dog teeth" and "eye teeth", come after the incisors, and there are four of them in the upper and lower jaws. Their ends are sharp, and they are useful for breaking the food. The molars are located behind the canines. The molars, which are different from each other in structure, are five in each half-jaw, two premolars and three molars, and a total of ten in one jaw. All premolars have two bumps each for chewing and clamping (Dentanorm, 2018).

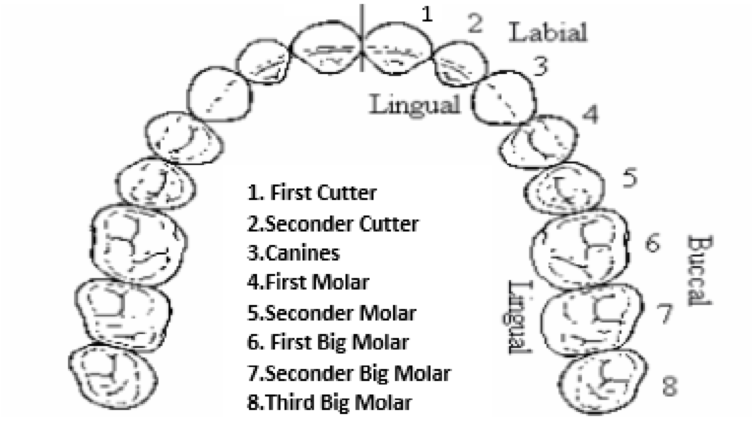

Fig. 2. Names and numbers of teeth inrelative to the midline (Dentanorm, 2018)

In the case of diet, some genetic factors and lack of care for teeth, cavities occur. In this case, its treatment is necessary. However, if it is not intervened in time, tooth deficiency occurs. Although it is quite troublesome and costly, the most preferred method is implanting treatment for missing teeth.

1.2 Treatment method with implant

In today's dentistry, implants have become routine applications in terms of aesthetics as well as fulfilling the functions of lost natural teeth. The amount, quality, and quantity of bone in the area where the implant will be placed are important criteria for implant success (Akça et al., 2002; Hasan et al., 2010; Neldam et al., 2010; Raviv et al., 2010). All dental implants used today are endosseous (intra-bone) implants in the form of tooth roots and are placed inside the jawbone like a real root. As seen in Fig. 3, the jawbone accepts the titanium (Ti-6Al-4V) screw, and the bone tissue grows on the screw. Tissue development is the component of the implant path that makes the implant look and feel like a natural tooth (Stevens et al., 1971). Prior to the advent of root-shaped endosseous implants, most implants were blade endosseous implants and subperiosteal implants that were fitted and screwed onto the jawbone to which the tooth frame was applied, due to the shape of the metal portion that remains in the bone. Additionally dental implants can be used to support many prostheses such as dental crowns, implant supported bridges and dentures (Stevens et al., 1971). A unique implant consists of a titanium screw with a rough outer surface or a smooth surface that resembles a tooth root. Most dental implants consist of commercially pure titanium, which has four classes according to its carbon and iron content. The use of Grade five titanium has increased in the recent past. Grade five titanium, Titanium 6Al-4V, is considered to exhibit the same degree of osseointegration as pure titanium. On the other hand, Ti6Al4V material has higher stress strength and fracture strength (Palmer, 2007; Karakurt, 2018). Today, implants are still made from pure (Class one-four) titanium, but some systems (Endopore and NanoTite®) use the Ti6Al4V alloy. Implant surfaces are treated by plasma spraying, anodizing, acid etching and sandblasting methods to increase the surface area and the integration potential (Nobel Active, 2008). The bone-acceptable biological material, titanium, is the metal most suitable for implant construction. It is also used in plates and screws applied in some fractures in the medical field. It is one of the most corrosion resistant metals. Since it is accepted by the human organism, there is no fear of rejection by the body (Lutton, 1998; Ben-Nissan, 1998). Titanium forms a stable and protective oxide film layer. However, this leads to absorption of proteins and differentiation in bone cells (Subaşı and Karataş, 2012).

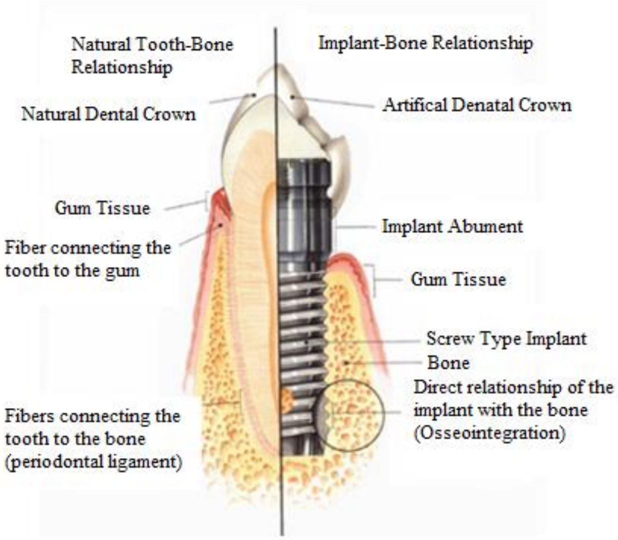

Fig. 3. Comparison of real tooth and implant (Lutton, 1998; Ben-Nissan, 1998)

Implants and implant-supported prostheses offer a comprehensive solution to all types of tooth loss and functional impairment. Single missing teeth can be replaced without disturbing healthy neighboring teeth using implant-supported prostheses. Implants can also be used to create fixed bridges for multiple missing teeth, eliminating the need for removable dentures. In cases of complete edentulism, fixed prostheses are a preferable alternative to removable prostheses (palate). These are the primary objectives of implants, as outlined by Stevens et al. (1971). Implants and implant-supported prostheses aim to provide a more natural and aesthetically pleasing appearance while maintaining stable teeth. Implants offer a high level of durability and prevent bone loss in the areas where teeth have been extracted or bone has thinned over time, which can cause variations to the facial profile. Additionally, the improved chewing function provided by implants leads to more balanced nutrition, eliminating stomach problems caused by poor chewing ability (Lutton, 1998; Ben-Nissan, 1998). Implants have some drawbacks such as higher cost compared to other treatment options, longer treatment duration, and the need for meticulous clinical and laboratory evaluation. In addition, proper oral hygiene, and cleaning procedures before and after implant placement are necessary. However, despite these drawbacks, implants are still attractive for scientists due to their significant advantages. There have been numerous studies conducted on implants to explore their potential and improve their functionality (Lutton, 1998; Ben-Nissan, 1998). Here are a few examples of recent studies on dental implants: Damlar et al. (2014) investigated the von Mises stresses that occur in response to the force applied during the chewing of the jaw by applying 100 N force on two commercial dental implants models. In their study Baştürk and Zor (2006), they carried out stress analysis by modeling an implant that can be applied to these tooth models and the effect of the horizontal angle of the tubercles on deformation and tension during loading and mounting the implant to the tooth. In dental models, the horizontal angles of the tubercle are 3°, 22°, 45°. The force that came to the tubercle on the upper surface of the tooth during chewing was applied vertically as 58 N

(≈ 6 kg). Göçer (2010) investigated the effects of two different commercial implant systems, one highly developed and a standard one, with different materials and force values in terms of geometry and strength. In the study, human biting force was used as a load. This value corresponds to a range from 222N to 522N in an adult male. This load was applied to make three separate angles (perpendicular to the surface, 60° and 30°) to the tooth surface. Küçük et al. (2009) and Dalkız et al. (2002) investigated the stress distributions of an implant in the second molar region of the lower jaw restored with a metal-ceramic crown under different loading conditions. Asar and Burgas (2009) examined the stress distributions caused by implant-supported wing bridges in different bone types. Arpa (2021) used implants made of titanium, zirconium, cobalt and gold, and prostheses made of zirconium and porcelain materials mounted on these implants. By exposing the different pairs of materials and the natural tooth to real-life conditions, he obtained numerical solutions for fifty-four different combinations using the Ansys 14.5 (CFX) program. They examined the temperature distributions under thermal conditions where there is water flow at 5 °C, 60 °C and air flow at -10 °C. Ormianer et al. (2009) experimentally examined the temperature rise in dental implants during the intake of hot beverages in vivo. A brief literature survey has revealed the importance of dental implants in dentistry. In the literature search, although only one (Arpa,2021) study was conducted under thermal conditions where water flow and air flow were performed as thermal analysis, the velocity or fluid flow rate of the liquid when drinking the beverage was specified.

In this study, a commercial implant was used to consider a more realistic situation; the convection and within the implant conduction effects were not neglected. Heat transfer occurs when drinking a beverage, considering the velocity and contact of the air entering the mouth with the liquid. In addition, the heat, and compressive strengths of titanium alloys (Ti-6Al-4V), which are often used in artificial dental crowns and tooth roots, were examined separately. The aim of this study is to investigate the thermal and mechanical properties of the Ti-6Al-4V alloy, the behavior that is occur when it is exposed to temperature and compression stress. In this context, it is aimed to determine the incompatibilities that may occur at the bone-implant interface and to emphasize that mechanical compatibility is an important issue besides biocompatibility.

Titanium alloys, which have superior properties, are widely used in various fields as well as dentistry. Ti-6Al-4V alloy has a wide range of applications due to many properties such as high strength, low density, and corrosion resistance. It is used in aviation, aerospace industry, medicine, and other industries. Table 1 shows the places where titanium alloys are commonly used.

Table 1. Applications of titanium alloys (Şap et al. 2019)

Applications	**Titanium Alloys**
Gas Turbine Engine Material	Ti-5,8AL-4Sn-3,5Zr-0,7Nb-0,5Mo-0,35Si-0,06C Ti-6Al2Sn4Zr-6Mo Ti-4Al-4Mo-2Sn-0,5Si
Airframe	Ti-10V-2Fe-3Al Ti-15V-3Cr-3Sn-3Al Ti-15Mo-2,8Al-3Nb-0,2Si
Ballistic Armor	Ti-6Al-1,8Fe-0,2Si
Geothermal and Offshore Pipes	Ti-6,8Mo-4,5Fe-1,5Al
Good Sporting Materials (light and high strength)	Ti-15V-3Cr-3Sn-3Al
Dental and Medical Applications	Vanadium-free ve Ti-6Al-4V, equivalent alloys
Medical Orthopedic Instruments	NiTi-Cu

2. Theory And Method

In this study, FE package software ANSYS was used. Temperature levels of 45º C, 10º C, along with the surface load of 100 N were applied to the three-dimensional dental implant prosthesis, respectively. The fluid (beverage + air) velocity was assumed as 1 m/s. Temperature and stress distributions were investigated at these input conditions. During the model design, the short dental implants in the literature were examined in detail and modeled appropriately and analyzed (Fig. 4).

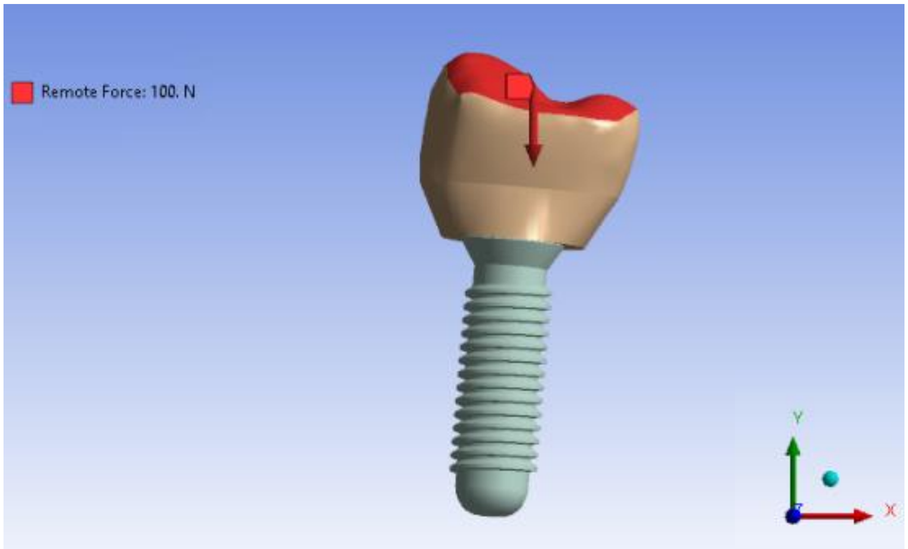

Fig. 4. The implant model used in the FE analyses and application of surface force

After the implant model was transferred to the Ansys Workbench program (Static Structural), the material properties of the tooth root and artificial tooth crown were entered. This process was performed by selecting the mechanical properties of each element on the model structure, if it is available in the material library of software package, and if not, by manually.

Two important material parameters, modulus of elasticity and the Poisson's ratio of the materials, are given in Table 2, and the thermal properties of titanium and dentin materials used in this study are given in Table 3, respectively.

Table 2. The mechanical properties of the materials used in the study (Şap et al. 2019)

Materials	**Elasticity Modulus (GPa)**	**Poisson Ratio (ѵ)**	**References**
Cortical Bon	10.7	0.30	Holmes et al., 1994; Meijer et al., 1994; Melo et al., 1995; Papavasilliou et al., 1996; Sertgöz, 1997; Barbier et al., 1998; Teixera, 1998; Akça et al., 2020.
Trabecular Bone	1.37	0.30	Holmes et al., 1994; Meijer et al., 1994; Sertgöz, 1997; Barbier et al., 1998.
Dentine	18.6	0.31	Melo et al., 1995; Geng et al., 2001; Aykul et al., 2002.
Titanium	115	0.35	Holmes et al., 1994; Texiera, 1998.
Acrylic	3	0.35	Tanino et al., 2007.
Mucosa	0.68	0.45	Pellizzer et al., 2010; Verri et al., 2011; Cunha et al., 2011.
Stainless Steel	190	0.31	Barao et al., 2008.
Nylon Resin	2.4	0.39	Pellizzer et al., 2010; Verri et al., 2011.

Table 3. The thermal properties of the materials used in the study (Matweb)

Material Properties	**Dentine**	**Titanium (Ti-6Al-4V)**
Density (kg/m^3)	2140	4430
Specific Heat (J/kgK)	1380	526
Thermal Conductivity Coefficient (W/mK)	0.57	6.7

Prior to numerical analysis, a validation study was conducted, and the result were compared with a study published in the literature (Göçer, 2010). The comparison between the results of the study conducted by Göçer (2010) and the results obtained from this study is shown in Fig. 5 as a bar graph. The difference observed between the results of the studies shown in the graph is due to the mesh structure of the studies and was in permissible level of error of 10%.

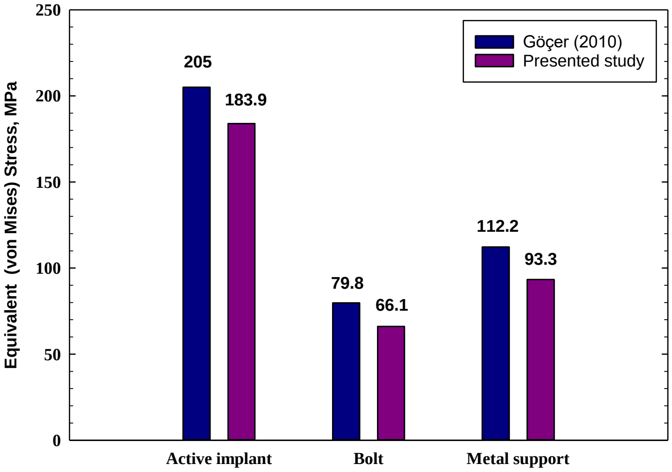

Fig. 5. A comparison of the literature of this study

The maximum and minimum principal stress values as well as the von Mises stress values of the implant's crown and root were calculated following loading, and the images were evaluated. A similar approach was considered in the thermal analysis as well.

After the material properties were defined in the program, the mesh structure was established. During the study, the curvature structure was used by choosing an advanced mesh structure. To obtain more realistic results, a mesh independent solution has been obtained. After the mesh structure of all surfaces of the model was created, the simulation step was started. At this stage, the force to be applied to the model was determined as 100 N based on the literature survey. By applying this force to the model, the deformation, and von-Mises (equivalent) stress variation on the implant were investigated.

In the thermal analysis performed in ANSYS (Fluid Flow), temperatures of 45^o C and 10^o C were applied to the model. For the highest temperature the temperature of food/beverage taken from a stove and the lowest temperature was accepted as the temperature of the beverage/food taken out of the refrigerator.

3. Results And Discussion

Although various cases have been studied, when the numerical solutions obtained were examined, it was noted that the solutions were very similar and therefore all the data were not mentioned in the current study. While evaluating the results; to make the implant and prosthesis temperature incompatible with real applications, it was assumed that they were equal to the body temperature.

3.1. Thermal Analysis

The data obtained from the numerical analysis is presented in the form of figures in sequence Fig. 6 and 7 depict the 3D temperature variations for the model at temperatures of 10^o C and 45^o C, respectively. As it can be noted, the temperature distribution seems to be uniform.

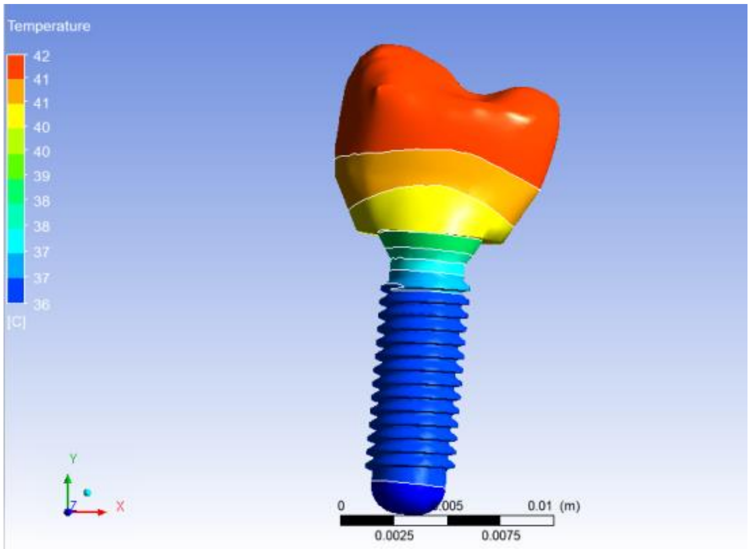

Fig 6. 3D temperature distribution on the implant at 45° C (hot drink case)

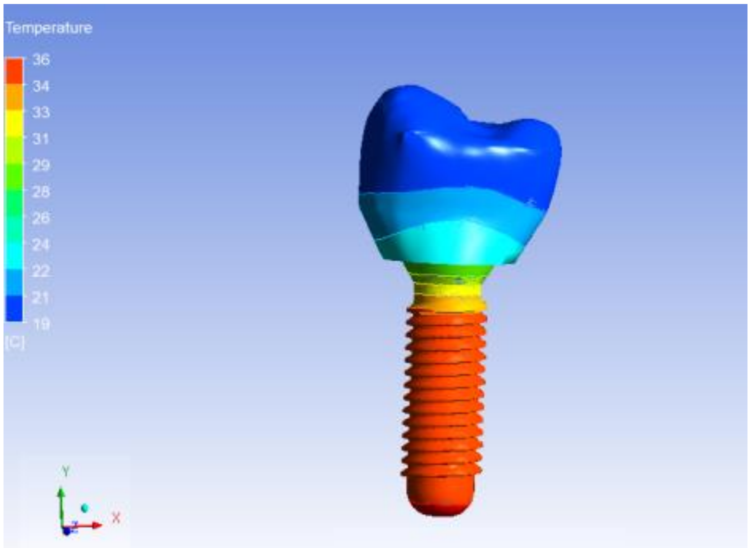

Fig 7. 3D temperature distribution on the implant at 10° C (cold drink case)

As seen from Fig. 6 and 7, it can be observed that the temperature is not instantly transferred to the implant root, thus preventing any potential problems that may occur in the gum and jawbone. The temperature variations in the implant prosthesis, as seen from Fig. 6 and 7, is lower in conductivity due to the artificial tooth crown being more insulated than the tooth root. Therefore, any potential issues such as cracking, breakage, and similar problems in the gum, jawbone, and artificial tooth crown caused by instantly variations in temperature have been prevented. This way, any deformations due to temperature variations that may occur between the implant prosthesis and the jawbone surface have been avoided.

For the 45° C temperature condition, the temperature distributions along the x, y and z sections are shown in graphs (Fig. 8).

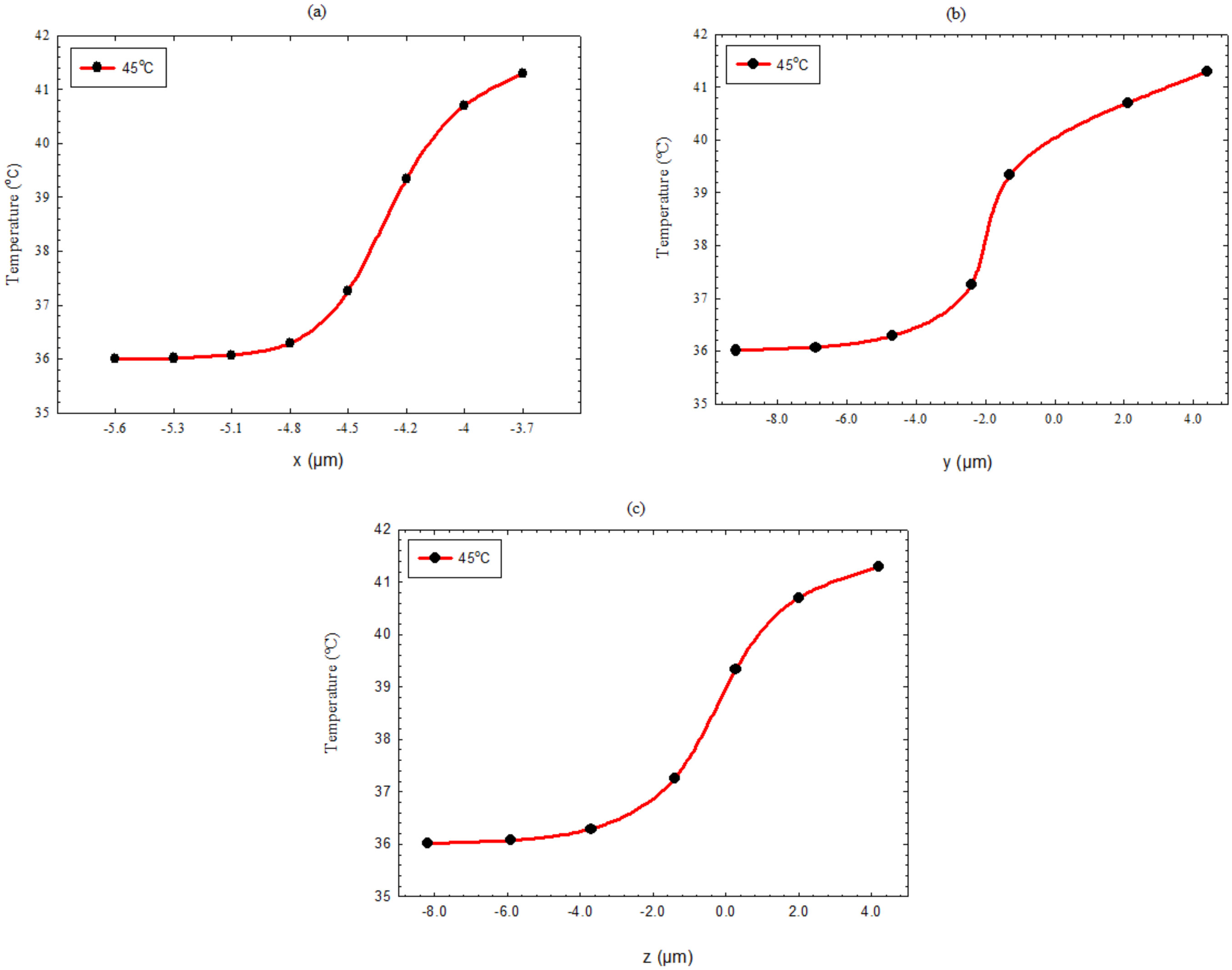

Fig. 8. Temperature distribution along the x-y-z-axis

The distribution with respect to the y-axis when a temperature of 45°C is applied is given in Fig. 8b. As seen from the graph, the temperature variations occur slowly up to 4.7 µm and then accelerates. This is because the artificial tooth crown is made of a more insulating material. The thermal conductivity coefficients of the crown materials used in dental implants are low. This is important in terms of reducing sensitivity caused by temperature variations in the mouth, as dental implants do not conduct heat well. The thermal conductivity coefficient of Ti-6Al-4V alloy is approximately in the range of 6.7-7.4 W/mK, while that of zirconium is approximately in the range of 2.5-3 W/mK. These values indicate that dental implants are an insulating material. The crown materials in dental implants are designed to reduce excessive sensitivity when in contact with hot or cold beverages or food.

Fig. 11 (a, b, c) show graphs showing the distance of temperature relative to the x, y, and z axes.

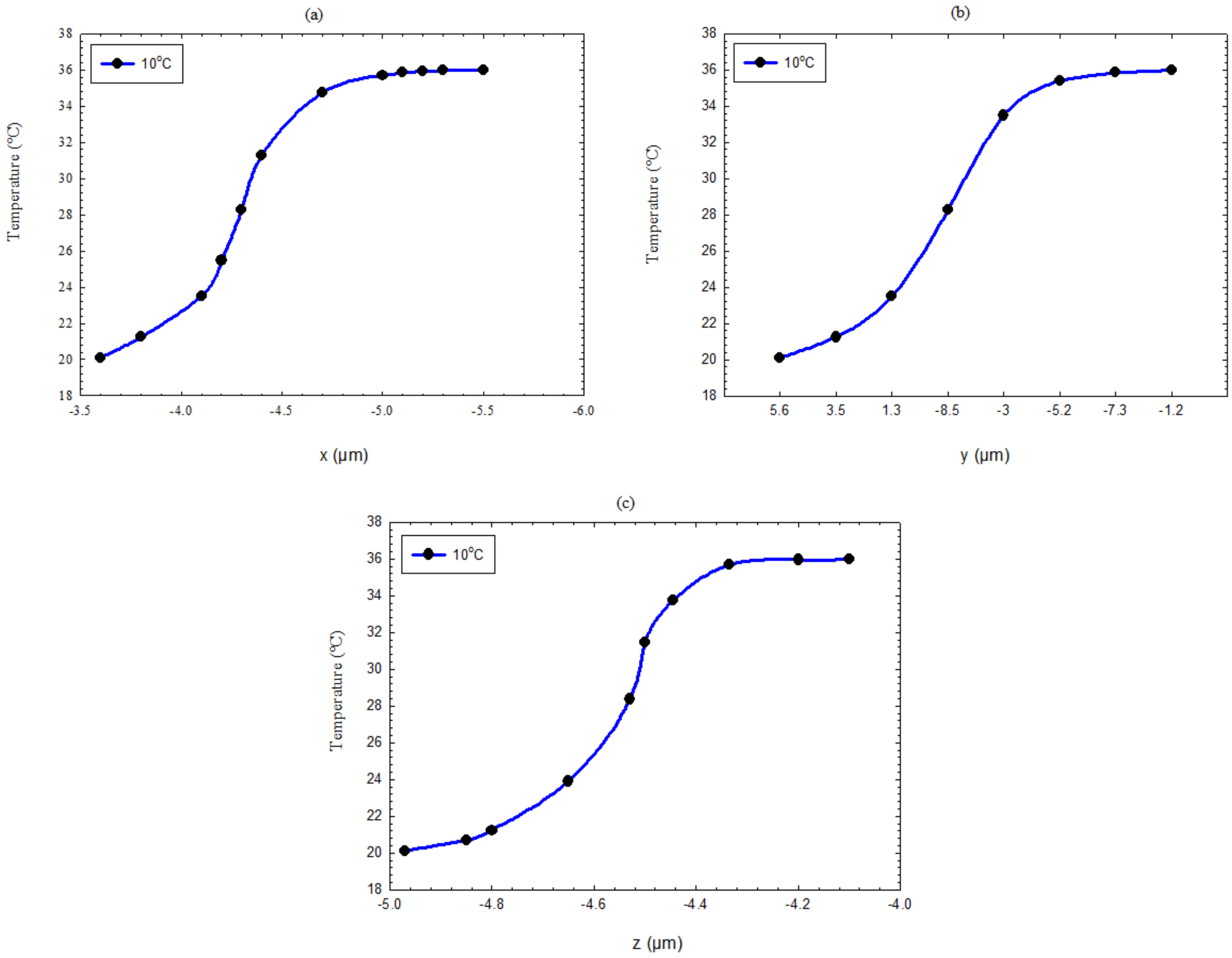

Fig. 11. Temperature distribution along the x-axis

As can be noted from the graphs, the temperature distributions are quite like each other. Because the artificial tooth crown is more insulating than the tooth root, the temperature is gradually transmitted up to the distance of -4.4 μm and then the temperature remains constant. The physical reason for this situation was previously explained in terms of heat transfer.

3.2. Mechanical Analysis

The deformation and von-Mises (equivalent) stress variations on the implant were examined by applying 100 N force to the model (Fig. 12 and 13). According to the implant stress value and color scale, the red areas for maximum principal stress and the blue areas for minimum principal stress are the regions where the lowest values are seen. According to the implant stress value, the red areas for maximum principal stress and the blue areas for minimum principal stress are the regions where the lowest values are recorded.

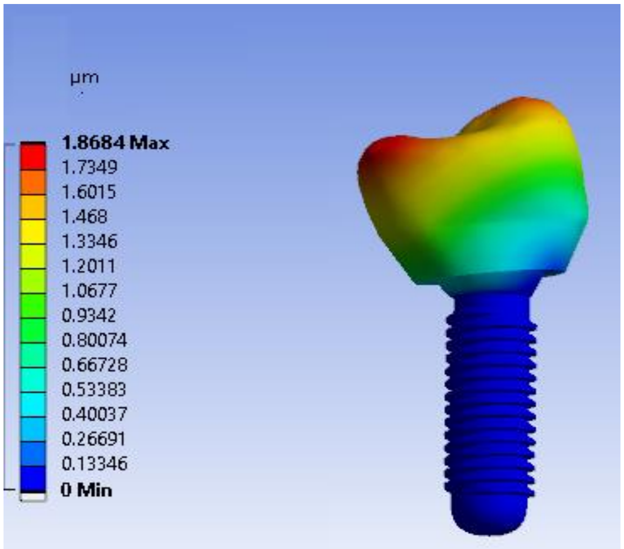

Fig. 12. Total deformation on the implant at different angles

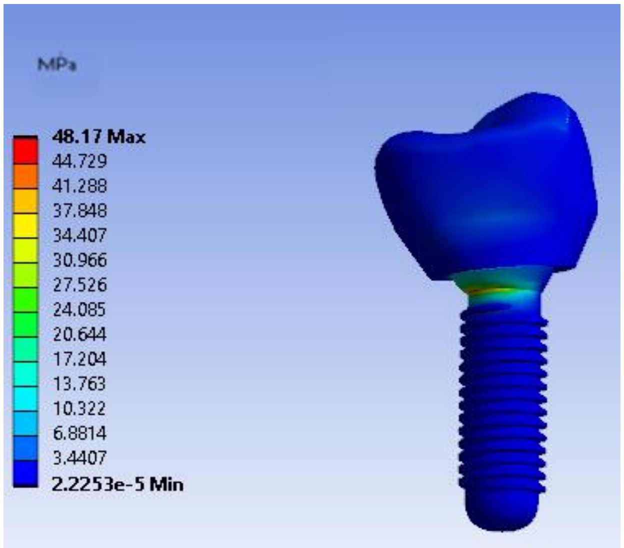

Fig. 13. von Mises (equivalent) stress distribution

Table 4 shows von Mises stresses and total deformation X-Y and Y-Z section views. As a result of the analysis, when the von Mises stresses on the implant are examined as seen in Table 4, it is seen that the maximum compression occurs in the tooth root. This can increase the risk of implant failure or various problems. Therefore, this stress caused by the incompatibility at the bone-implant interface can prevent the implant from functioning properly. In addition, since the stresses occurring in the tooth root do not reach the compressive strength, it is seen that the implant is durable under static conditions. As the temperature increases, the von Mises stress decreases due to the expansion of the material, while its displacement increases (Taşdemir, 2021).

Table 4. von Mises stresses and total deformation cross-section

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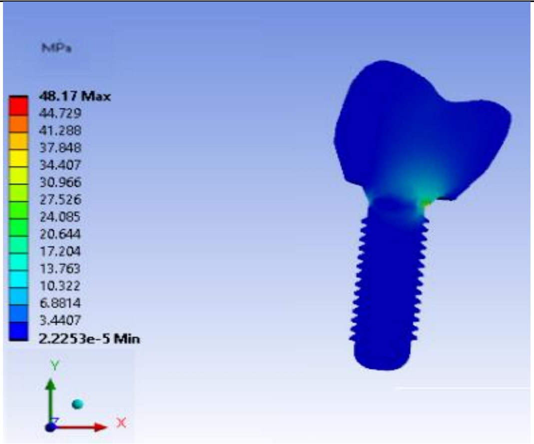
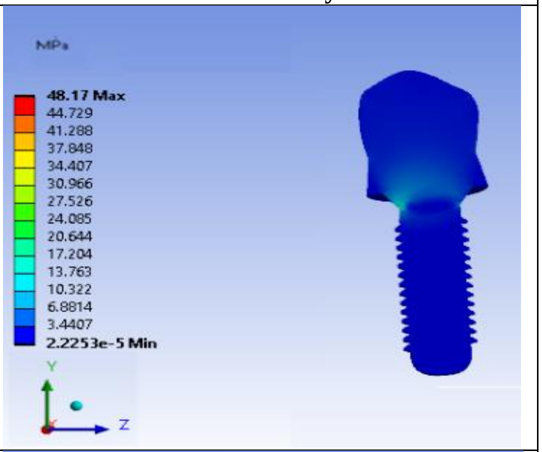
<tr><th></th><th>Cross section x-y</th><th>Cross section y-z</th></tr>
<tr><td>von Mises</td><td>
</td><td>
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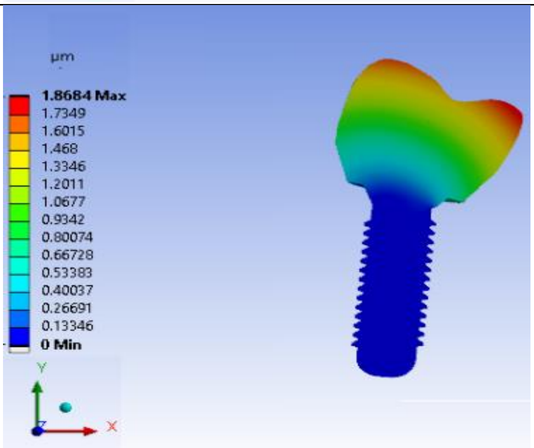
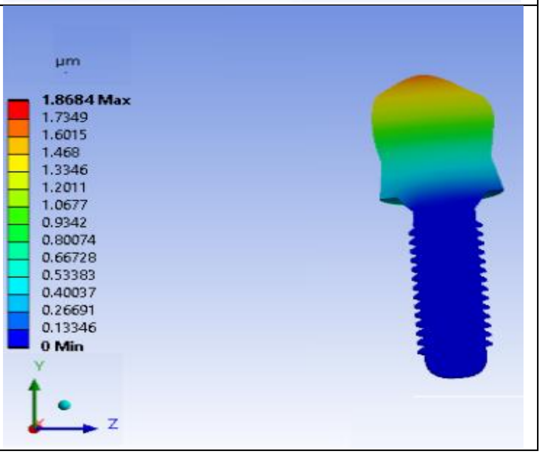
<tr><td>Deformation</td><td>
</td><td>
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When the total deformation on the implant is examined in Table 4, it is seen that the highest amount of deformation with 1.868 µm is concentrated in the artificial tooth crown of the tooth and decreases towards the root of the tooth. Fig. 14, 15, and 16 show the variation of von Mises stresses with respect to the x, y and z axes.

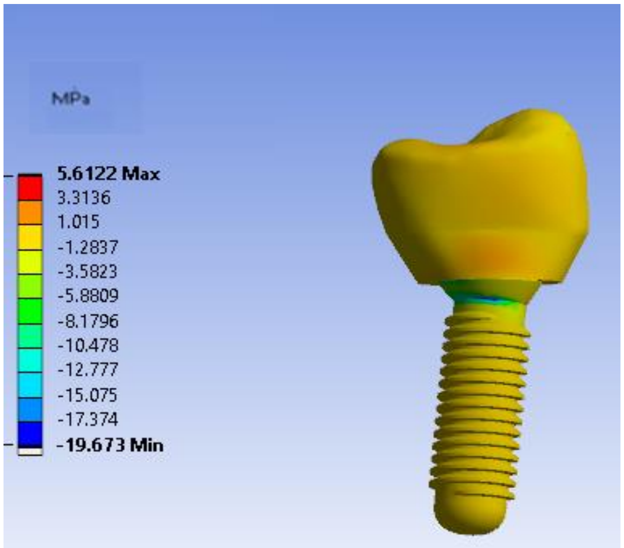

Fig 14. von Mises stress distribution in the x-axis

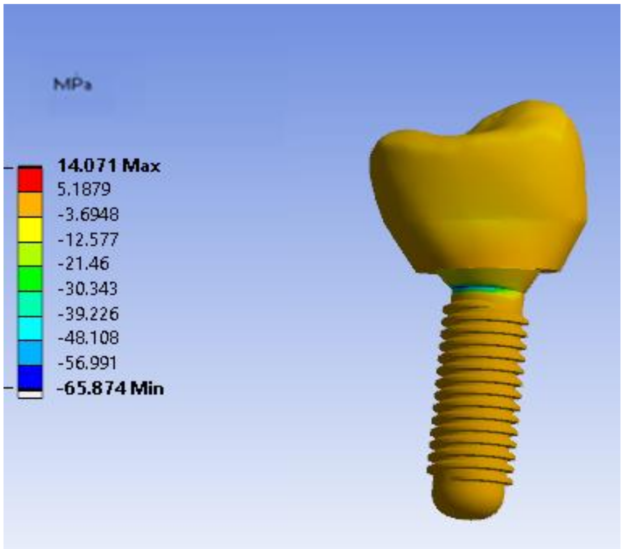

Fig. 15. von Mises stress distribution in the y-axis

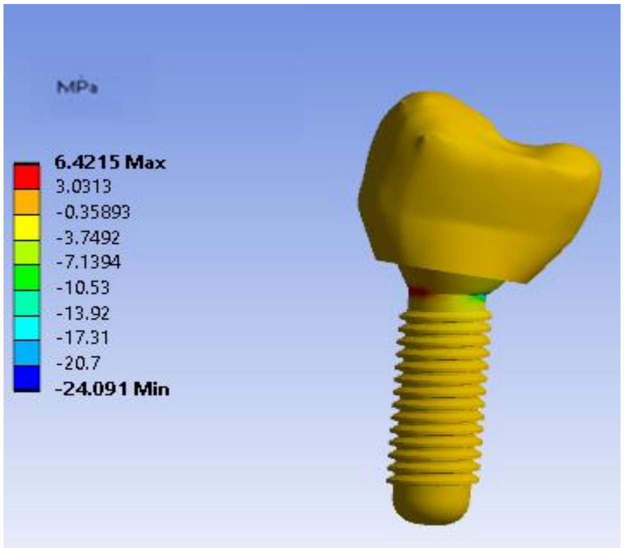

Fig. 16. von Mises stress distribution in the z-axis

As a result of the analysis, as can be seen in Fig. 14, 15 and 16, the maximum von Mises stress was realized as 14 MPa. The reason for this is that 100 N force was applied to the implant prosthesis in the y-direction.

4. Conclusion

Theoretical (numerical) and experimental analysis methods are used to evaluate the stresses caused by chewing forces and temperature in scientific studies aimed at developing medical treatments. Despite its limitations, the finite element stress analysis method can accurately and completely model complex geometries and material properties. Additionally, this method is widely used due to its advantages such as the ability to make variations in the generated model, obtain stress type, distribution, and deformation together and very accurately, present stresses in understandable numerical values, and easy control of the experimental aim. Therefore, the finite volume stress and thermal analysis method has been preferred in the study.

- Upon analyzing the results of the von Mises stress distribution and total deformation analysis showed that the implant prosthesis exhibited high stress and compressive strength. It was also observed that the artificial dental crown covered a significant portion of the total deformation, while the tooth root showed minimal deformation. These results agreed with those reported in a previous study.
- It was determined that the highest stress values upon loading occurred in the crown and the lowest stress values occurred in the root.

- According to the results of the study, while a uniform distribution was observed in three principal axes in thermal examination of the implant, non-uniform values were detected in three principal axes in mechanical examination.
- The chewing force applied due to the tooth geometry causes non-uniform stress distribution in all axes, and this reveals the importance of mechanical compatibility between the implant root and the bone interface. A similar situation will occur in the stress change due to temperature change.
- Implants can be exposed to stress values up to 48.17 MPa, which can lead to problems at the implant-bone interface, especially in the presence of conditions such as osteoporosis and menopause that cause bone loss and affect differentiated bone cells. Therefore, mechanical compatibility as well as biocompatibility is very important for the success of dental implant prosthesis.
- Artificial tooth crowns and tooth roots are usually made using titanium alloys (Ti-6Al-4V). Nevertheless, these alloys may cause problems at the implant-bone interface due to factors such as loss of bone volume and bone resorption or differentiation in bone structure. Therefore, the design and selection of dental implant prosthesis materials should be made by considering the bone structure of the patient.
- It has been observed that materials commonly used in dentistry, such as titanium alloys (e.g., Ti-6Al-4V), have insulation properties and exhibit durability characteristics depending on temperature changes and compressive stress. Taking these properties into consideration, producing materials for dental applications that are both cost-effective and consider the issue of bone loss could contribute significantly to the economy of our country.

Performing this study time-based and simultaneously will allow more detailed results to be obtained. In addition, it is important to include statistical study on the patients with bone loss and bone diseases due to osteoporosis, menopause.

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