

CHARACTERIZATION OF MECHANICAL PROPERTIES: TITANIUM VS. STEEL IN THE BATTLE OF ORTHODONTIC MINI-IMPLANTS

Tinela Panaite¹, Cristian Liviu Romanec^{1*}, Carmen Savin¹, Mihnea Iacob¹, Raluca-Maria Vieriu¹, Alice Chehab¹, Irina Nicoleta Zetu¹, Carina Balcos¹

¹Department of Oral and Maxillofacial Surgery, Faculty of Dental Medicine, "Grigore T. Popa" University of Medicine and Pharmacy, 16 Universitatii Str., 700115 Iasi, Romania; tinela-panaite@umfiasi.ro (T.P); carina.balcos@umfiasi.ro (C.B.); carmen.savin@umfiasi.ro (C.S.); mihnea.iacob@umfiasi.ro (M.I); liviu.romanec@umfiasi.ro (C.L.R.); raluca-maria.vieriu@umfiasi.ro (R.M.V.); alice-chehab@umfiasi.ro (A.C); irina.zetu@umfiasi.ro (I.Z.)

* Corresponding author: Cristian Liviu Romanec: Liviu.romanec@umfiasi.ro (C.L.R.)

ABSTRACT

The mechanical properties of orthodontic mini-implants play a critical role in their performance, stability, and durability during treatment. This study investigates the tensile behavior of mini-implants fabricated from titanium alloy (Ti6Al4V) and stainless steel (316L) through tensile testing. The experiments were conducted using the INSTRON 34SC-5 servohydraulic system under controlled conditions to evaluate parameters such as ultimate tensile strength (σ_{UTS}), yield strength (σ_y), elongation at fracture, and modulus of elasticity. The results demonstrate that titanium mini-implants exhibit higher deformation energy storage and superior ductility compared to stainless steel, with σ_{UTS} values of 488 MPa and 462.6 MPa, respectively. However, both materials displayed predominantly brittle fracture behavior. Significant differences in elongation at fracture highlight the titanium alloy's enhanced capacity to absorb energy through plastic deformation, ensuring greater reliability under mechanical forces. This study emphasizes the importance of tensile strength and ductility in material selection for mini-implants, as they directly influence stability, resistance to mechanical stresses, and clinical performance. Insights gained from tensile testing contribute to optimizing the design and manufacturing of mini-implants, ensuring their integrity under orthodontic loads and improving treatment outcomes. The findings underscore the potential of titanium alloys in providing superior mechanical properties, making them the preferred choice for advanced orthodontic applications.

Keywords: Orthodontic Mini-Implants; Tensile Testing; Titanium Alloy (Ti6Al4V); Stainless Steel (316L); Mechanical Properties; Tensile Strength

Introduction

The use of tensile tests to characterize the mechanical properties of orthodontic mini-implants provides significant information regarding their stability, primary stability, and changes in properties due to thermoforming processes. Tensile testing is a fundamental mechanical test used to evaluate the behavior of materials under tension. It involves applying a controlled tensile force to a specimen to assess its response to stretching or elongation until reaching the breaking point.

Tensile testing represents the fundamental evaluation of a material, aiming to determine its key mechanical characteristics. This test involves subjecting samples of various dimensions to tensile forces, gradually and continuously applying a load without shocks along their longitudinal axis, usually until rupture occurs. During the testing process, the sample undergoes deformations such as elongation, contraction, and bending, ultimately leading to fracture. The deformations corresponding to different tensile force

values are measured throughout this process.

Tensile testing provides valuable information about the mechanical properties of a material, including: tensile strength, elongation, and modulus of elasticity. In the context of orthodontic mini-implants, tensile testing is essential for characterizing the mechanical properties of the materials used. The ultimate tensile strength of the implant material is particularly important, as it indicates the maximum stress the material can withstand before breaking under tensile load. Elongation at break provides information about the material's ductility, which is essential for evaluating its ability to deform before fracturing.

The tensile strength of orthodontic mini-implants is a crucial factor in orthodontic treatment. Motoyoshi et al. highlighted the high stability of mini-implants during the application of orthodontic forces (1). Chen et al. found that the tensile strength of mini-implants placed in the infrazygomatic crest was significantly higher than the applied orthodontic force, indicating strong resistance to tensile loading (2). Katić et al. examined the geometric design characteristics of orthodontic mini-implants and their correlation with the maximum insertion torque, providing insights into the structural aspects that influence breaking strength (3). These studies collectively contribute to understanding the breaking strength of orthodontic mini-implants under tensile loading, considering factors such as insertion torque, design characteristics, and patient-related variables.

The breaking strength of mini-implants varies depending on the material from which they are made. Mini-implants are typically made of titanium alloy, especially pure grade V titanium (4). Studies have shown that the mechanical strength of mini-implants is influenced by the material and internal microstructure (5-7). The Ti6Al4V alloy has been shown to have higher mechanical strength than pure titanium, making it the most suitable for the small diameter of mini-implants (8,9). Breaking strength varies depending on the material used, with titanium alloy, particularly pure grade V and Ti6Al4V alloy, being the most commonly used materials. Characterization of mechanical properties: Performing tensile tests for titanium alloy and stainless steel mini-implants to characterize their mechanical properties, such as tensile strength, elongation, and deformation at rupture. Determining tensile strength: Measuring tensile strength values for titanium alloy and stainless steel mini-implants under controlled conditions. Analyzing mechanical properties: Evaluating the results of tensile tests to analyze the mechanical properties of mini-implants, including deformation at rupture, stretchability, and tensile behavior. Comparing material performance: Comparing the results of tensile tests between titanium alloy and stainless steel mini-implants to evaluate their relative performance under tensile loads. These general and specific objectives aim to achieve a comprehensive understanding of the mechanical behavior of orthodontic mini-implants, contributing to their optimization in clinical practice and technological development in orthodontics.

Materials and Methods

10 self-drilling mini-implants (Ti-6Al-4V):Dimensions: 2.0 mm (diameter) $\times$ 10 mm (length)

Manufacturer: Jeil Medical Corporation, Dual Top Anchor System

10 mini-implants (316L stainless steel):Dimensions: 2.0 mm (diameter) $\times$ 12 mm (length) Manufacturer: Leone

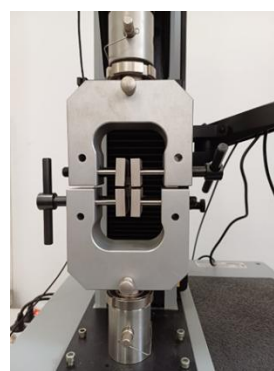
The INSTRON 34SC-5 servohydraulic testing system (fig.1.a-b) provides comprehensive solutions for conducting static and dynamic tests on metallic and non-metallic materials, including both conventional and advanced

materials, on individual samples as well as components. The device has a loading capacity of up to 100 kN, offering a generous working space between the crossheads, as well as high stiffness and precision in alignment processes.

Using precision mechanical systems and advanced features of the digital controller and Dynacell 34SC-5™ load cell, this system meets strict requirements for both dynamic and static tests. The INSTRON 34SC-5 universal testing machine for static and fatigue testing excels in maintaining stable measurements, including force, displacement, and deformation.



(a)



(b)

Figure 1. Equipment used for tensile testing (a) Instron Software; (b) INSTRON 34SC-5 Servohydraulic Testing System.

The tensile tests performed on the mini-implant samples were conducted using the INSTRON 34SC-5 servohydraulic testing equipment (fig.1-2) available in the Materials Strength Laboratory of the Faculty of Mechanics, “Gheorghe Asachi”

Technical University of Iași. The test was carried out at ambient temperature, with a loading speed of 0.5 N/min, optimized to allow the acquisition of as many essential points as possible from the characteristic σ - ϵ curve (stress-strain curve).



Figure 2. Tensile strength measuring device Instron 34SC-5.

The mini-implant samples were embedded in an acrylic mass to facilitate clamping in the apparatus (fig.3) and were subjected to tensile testing at a constant speed of 2 mm/min, until rupture occurred.



Figure 3. Samples embedded in acrylic mass for tensile testing.

The principle of tensile testing measurement is illustrated in Figure 4. The graph representing the relationship between the relative dimensions σ (stress) and ϵ (strain) is distinctive for each category of

materials and is referred to as the characteristic curve of the material (in this case, under tensile testing). This curve provides a series of relevant information

about the respective material properties, as will be detailed further.

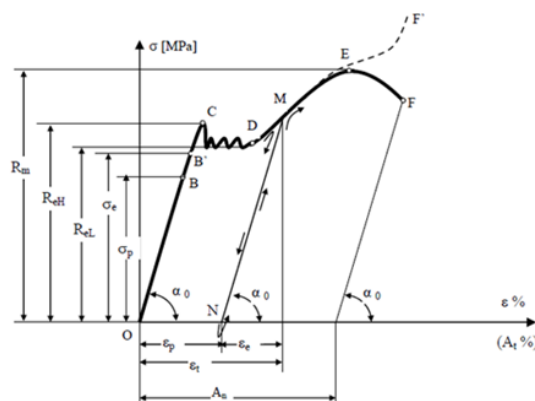


Figure 4. Characteristic tensile curve of steel materials (10).

Results

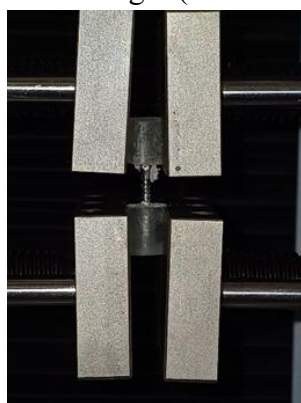
To facilitate tracking of measurement values, Table 1 provides a summary of the main parameters determined for the two types of samples following the static tensile testing. The primary parameters considered are:

Average diameter (dmed) [mm],

Longitudinal modulus of elasticity ($E \cdot 10^5$) [N/mm²],

Yield strength (σ_y/σ_c) [N/mm²],

Ultimate tensile strength (σ_{UTS}/R_m) [N/mm²].



(a)



(b)

Figure 5. Samples with the mini-implant inserted in the tensile testing apparatus (a) before and (b) after the tensile test experiment.

Differences are observed between the two types of samples made from titanium alloy and stainless steel, as summarized in Table 1, regarding ultimate tensile strength and yield strength.

Table 8.1. Results obtained from tensile testing

Material	dmed [mm]	$E \cdot 10^5$ [N/mm ²]	σ_y (σ_c) [N/mm ²]	σ_{UTS} (Rm) [N/mm ²]
Steel-316L	2	206.2	442.2	462.6
Ti6Al4V	2	108.4	425.1	488.0

The characteristic curves obtained from the tensile testing of titanium and steel mini-implant samples are presented in Figures 6-7.

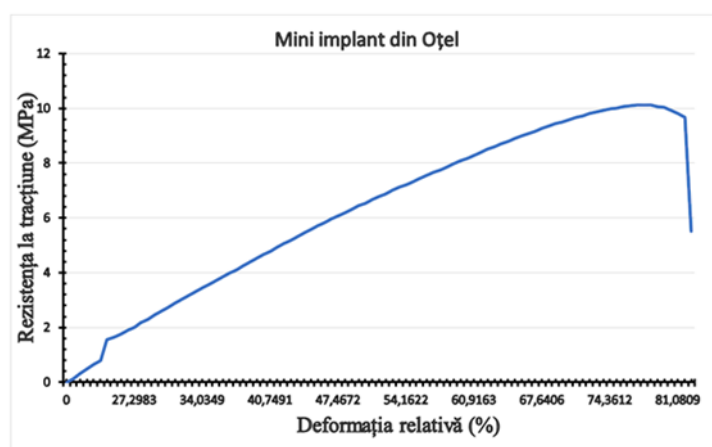


Figure 6. Characteristic tensile curve for the steel mini-implant.

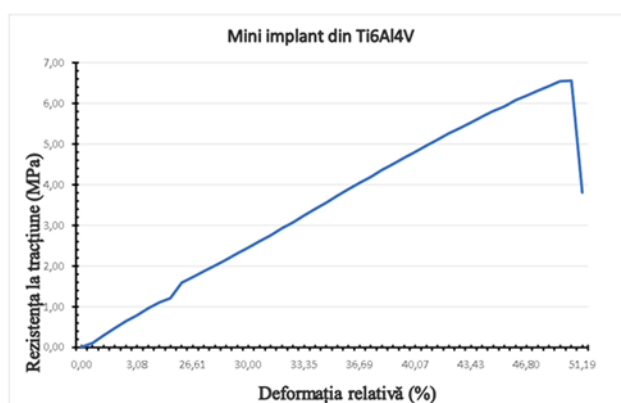


Figure 7. Characteristic tensile curve for the Ti6Al4V mini-implant.

Analysis of the Tensile Behavior of Mini-Implants

- Initial linear region:** The curve begins with a linear increase in force as deformation (elongation) increases. This corresponds to the elastic deformation of the material. In this region, the material behaves according to Hooke's Law, where stress is directly proportional to strain.
- Yield point and plastic deformation:** Around 45% deformation, a deviation from linear behavior occurs. This point represents the yield point.
- Tensile strength:** This is the maximum stress the material can withstand before failure.
- Necking and fracturing:** This is caused by localized thinning (necking), leading to fracture.
- Ductility and brittle behavior:** The curve's behavior suggests that the material is ductile (Figure 6).

Discussions

The tensile test was conducted to determine specific material characteristics that can only be obtained through this method. Thus, from the tables generated by the testing machine, characteristics such as tensile strength, elongation at fracture, yield strength, and longitudinal modulus of elasticity were recorded for each sample. Samples made of titanium alloy and stainless steel were tested until rupture. The results are presented in Table 1, Figure 6, and Figure 7, with the following observations:

1. The average tensile strength values (σ_{UTS}) are similar: 488 MPa for the titanium sample and 462.6 MPa for the steel sample.
2. Significant differences are observed regarding elongation at fracture.
3. These differences influence the total energy accumulated until rupture (elastic and plastic), with a higher percentage resulting from plastic deformation energy.
4. The total energy accumulated until rupture (elastic and plastic) is greater for the titanium sample, reflecting a superior capacity for energy storage during deformation.
5. It was found that both samples exhibited predominantly brittle fracture.

Tensile strength is an essential factor in determining the durability and reliability of materials. According to Arifin et al., tensile strength represents the measure of a material's capacity to resist rupture when subjected to tension (11). Knowing the maximum stress the implant material can

endure before breaking under tensile load is crucial for several reasons.

- First, it allows for the evaluation of stress distribution within the implant material, particularly in the implant neck area, which is a critical zone susceptible to high stresses during load application (12,13).
- Second, understanding the maximum stress capacity of the implant material is essential for assessing the implant's vulnerability under various loading conditions, such as compression in compact bone and tension at the interface between cortical and trabecular bone (14).
- Third, this knowledge is vital for predicting potential overloading and the risk of implant failure, especially in areas where stress concentrations are high (15,16).

The maximum stress the implant material can sustain is crucial for evaluating the impact of various design parameters, such as diameter, length, and taper, on deformations in the alveolar ridge and bone quality, as well as for assessing the influence of bone density on stress distribution in the bone surrounding the implant (17,18). Elongation at fracture is a crucial measure of the ductility of implant materials, indicating their ability to undergo significant plastic deformation before fracturing (19,20). High values of elongation at fracture indicate good ductility, allowing the material to absorb energy through plastic deformation and reducing the risk of sudden failure (21). This property is particularly important for orthodontic mini-implants, which must withstand mechanical forces and deform

without fracturing to ensure stability and longevity during orthodontic treatment (22,23). The choice of materials for orthodontic mini-implants is influenced by the need for high tensile strength to ensure the implants' resistance to mechanical forces exerted during treatment (24). Materials with high tensile strength are preferred as they provide adequate stability and resistance to deformation, reducing the risk of implant failure and displacement (25). High tensile strength is essential to ensure the integrity of implants during orthodontic loading and occlusal forces, contributing to their long-term reliability and performance (25). Elongation at fracture is a critical factor in selecting materials for orthodontic mini-implants because it reflects the material's ductility and its ability to undergo plastic deformation before fracturing (25). Materials with sufficient elongation at fracture are preferred to ensure that implants can deform without fracturing under orthodontic forces, reducing the risk of sudden failure and improving their reliability during treatment (25). Ductility is essential for preventing premature failure, adapting stress concentrations, and ensuring the stability of implants under cyclic loading (24). The mechanical characteristics of tensile strength and elongation at fracture significantly influence the selection of materials for orthodontic mini-implants. The need for high tensile strength and sufficient elongation at fracture dictates the selection of materials that can provide the stability, reliability, and performance required for successful orthodontic treatment. Tensile testing results play a crucial role in improving the design and manufacturing of orthodontic mini-implants. Tensile testing provides valuable data about the mechanical properties of the materials used in mini-implants, such as ultimate tensile strength, fracture resistance, and elastic modulus. This information is crucial for

optimizing mini-implant designs to ensure they can withstand the forces exerted during orthodontic treatment (26). By understanding the mechanical behavior of various implant designs, manufacturers can adapt design parameters to enhance primary stability, which is essential for the success of orthodontic mini-implants (27, 28). Tensile testing can validate the mechanical integrity of mini-implants produced using advanced manufacturing techniques, ensuring they meet the necessary strength and stability requirements for clinical use. Tensile testing results are vital in improving the design and manufacturing of orthodontic mini-implants, offering valuable insights into material behavior, primary stability, and the interaction between implant design and bone properties. This knowledge is essential for developing mini-implants that can withstand orthodontic forces and for improving overall clinical outcomes.

Conclusions

Based on the results, it can be concluded that titanium and steel mini-implants have different capacities for withstanding external loads and storing deformation energy. The titanium mini-implant demonstrates a greater ability to withstand external loads and store deformation energy compared to the steel mini-implant. The tensile test provides vital information for evaluating and selecting materials used in the fabrication of orthodontic mini-implants: Strength evaluation: Assessing tensile strength provides a measure of the mini-implants' ability to withstand the forces applied to them during clinical use. Understanding the level of strength is essential to ensure that the mini-implants are robust enough to resist environmental stresses. Ductility determination: Elongation at fracture provides insights into the material's ability to undergo plastic deformation before breaking. For mini-

implants, it is important to choose materials that are ductile enough to allow handling during insertion and adaptation to positional changes within the oral cavity. Fracture behavior: The type of fracture observed during testing—whether

brittle or ductile—provides clues about the material's behavior under extreme stress. Choosing a material with appropriate fracture behavior can help prevent premature failures of mini-implants during use.

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