

ASPECTS CONCERNING THE MECHANICAL RESISTANCE OF THE ALIGNER MATERIALS

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ABSTRACT

Aim of the study The most commonly materials in aligners technology are polyurethane and glycol-modified PET, but the thermoplastic polyurethanes (TPU) are used by the most famous brands of aligner production – although, the properties of materials used for their fabrication remain one of the most essential aspects in determining their mechanical and clinical features. **Materials and methods** The objective of this study is to determine the tensile strength and elasticity of different types of materials used in the manufacture of aligners with a performant mechanical testing system, with a specific software, on eleven samples made from different materials and different thickness, with special marks, in order to determine the mechanical resistance and elasticity until the breaking moment. Data were registered and the software elaborated the parameters and the curves for specific stress-strain, and the variations of stress in relation to the longitudinal and transversal specific deformation. **Conclusions** There is noticed the fact that, when the stress reaches a value of approx. 20 MPa and the longitudinal specific deformation of approx. 1%, is observed a curvature of the variation graph, signifying the transition to the plastic range of the material, and the breaking moment occurs at stress values of approximately 45 MPa, longitudinal specific deformation of 3% which shows the brittle nature of the material.

Key words: mechanical resistance, tensile strain, aligner materials

INTRODUCTION

Searching the specific literature and catalogues of various aligner producers, PET-G is currently utilized by the majority of manufacturers, but there is a variety of materials used as - polypropylene, polycarbonate (PC), thermoplastic polyurethanes (TPU), ethylene-vinyl acetate and. The type introduced in 2013 was polyurethane material and became the best material for aligner therapy. Clear aligners

are available in a variety of thicknesses, ranging from 0.50 mm to 1.5 mm. This, like the building material, can have an impact on their mechanical qualities and, as a result, their performance. [1].

The materials used to manufacture the aligners are generally derivatives of polyvinyl chloride, polyethylene terephthalate glycol (PET-G), polypropylene (PP), polycarbonate (PC), thermoplastic polyurethanes (TPU),

ethylene-vinyl acetate (EVA) and many more (Lombardo et al., 2015).[2] The most commonly used materials in aligners are polyurethane and glycol-modified PET.

Polyurethane sheet is the most suitable option - the polymer type material is formed from isocyanate with a polyol in the presence of catalyst and some additives. For the first time, an aligner was obtained from a single layer of rigid polyurethane, but later, the thermoplastic type material showed much improved flexibility and tear resistance.

Among these materials, PETG is widely used for its excellent impact and tear strengths, barrier properties, chemical resistance, and transparency. [3] In addition, TPU with greater elasticity is used by the most famous brands of aligner production to obtain more predictable orthodontic movements by applying light and constant forces. Multi-hybrid materials have also been developed to improve the physical properties of the single material [4,5].

Although the clinical efficacy of clear aligners can be affected by a multitude of factors [6–10], the properties of materials used for their fabrication remain one of the most essential aspects in determining their mechanical and clinical features [11].

MATERIALS AND METHODS

Our study aimed to determine the tensile strength and elasticity of different types of materials used in the manufacture of aligners, usually made either through the thermoforming process or 3D printing.

The mechanical testing system used was of the Instron® type (INSTRON - MODEL 34SC-5; USA), figure 1. To determine the applied loading force, a force transducer was used, which allows force measurements up to 5 kN, with an accuracy of 0.5%, in

accordance to ASTM D790 (495) standards (figure 2). The speed of force application can be adjusted in the range 0.05-1016 mm/min, with an accuracy of 0.2%. The axial displacement/strain was measured using the numerical axis of the testing machine with accuracy of 0.015 mm.



Fig. 1. The mechanical system (testing machine) used for axial tensile testing is INSTRON - 34SC-5.

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Fig. 2. The force transducer (cell) used in the testing machine

The specific strain was automatically calculated by the testing machine software based on data provided by the linear extensometer mounted on the test specimen, Figure 8. Data acquisition and processing were performed using the integrated Instron Bluehill® software, Figure 3, which meets the needs of a wide range of applications, including plastics, metals, elastomers, adhesives, and others.



Fig. 3. BlueHill software installed on the computer testing system

Testing the samples was carried out in the order of the study batches, for each uniaxial tensile test. The magnitude of the axial loading forces was chosen so that the tested samples remained in the elastic range for the samples with strain gauge marks, and exceeded the breaking limits for the other samples. Confirmation of compliance with the elastic limits was achieved by visual inspection of the graphs of dependence between deformation and force, as well as by the repeatability of the hysteresis cycle, each test.

An image of the initial samples, with the protective foil, before stressing can be seen in figure 4. From the initial circular shape, given the dimensions required for the samples (the need to be clamped in the jaws of the testing machine, etc.), only two flat samples like those in figure 4 could be cut and processed.



Fig. 4. Samples cut and processed from the initial circular shape (with protective foil)
A total of 11 samples were stressed until failure: 4 samples made from 0.8 mm thick

discs, 4 samples made from 0.5 mm thick discs and three other samples taken from discs with a different material than the first ones and having a thickness of 0.8 mm. (Figure 5)

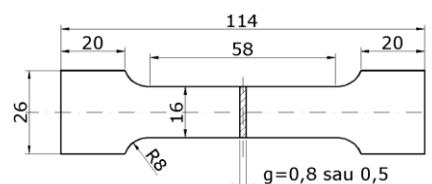


Fig. 5. Shape and dimensions of tensile specimens

4 samples were made with the shape and dimensions given in figure 5. First, the samples were cut into parallelepiped shapes, after which, by milling at low cutting parameters and with emulsion jet cooling, they were given the shape with a calibrated portion of 16x54 mm. The wider area at the ends was necessary for clamping in the jaws and the calibrated portion is necessary for obtaining the break here, for mounting the extensometer and, respectively, for gluing the strain gauge marks.

As previously mentioned, 11 samples were stressed to failure, figure 6.a, and two samples, on which strain gauge marks were previously glued, figure 6.b, were stressed in the elastic range.

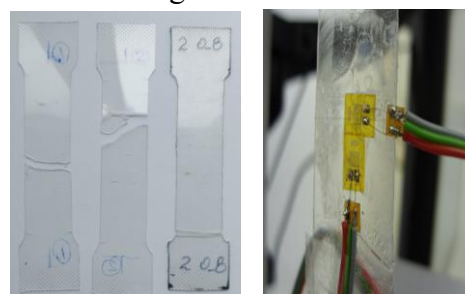


Fig. 6. Specimens subjected to uniaxial tension: a) until rupture/failure; b) in the elastic range

On the 11 samples stressed to failure, for the acquisition of data with which the

specific longitudinal deformation can be calculated, as the extensometer was mounted (figure 7).



Fig. 7. Testing the samples, on the Instron type machine with the extensometer mounted

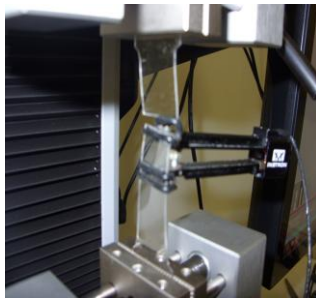


Fig. 8. Image of samples breaking in the testing machine

RESULTS AND DISCUSSIONS

The tension is calculated with the relation:

$$\sigma = F/A_0$$

where F is the force provided by the testing machine and A_0 is the value of the initial cross-sectional area of the sample.

The specific linear deformation is given by:

$$\varepsilon = \Delta l/l_0$$

where Δl is the variation of the given length between the extensometer arms and l_0 is the initial length set for the extensometer arms which is, in this case, 12.5mm.

Figures 9 and 10 show the stress-strain curves obtained for that 4 samples - it should be noted that the lines in these figures are drawn automatically by the testing machine software. The line on the

left is called the elasticity line and shows the longitudinal modulus of elasticity, and the line on the right is drawn at a distance of 0.02% with respect to the longitudinal specific strain and parallel to the elasticity line. This latter line shows, at the intersection with the characteristic curve, the yield point of the material.

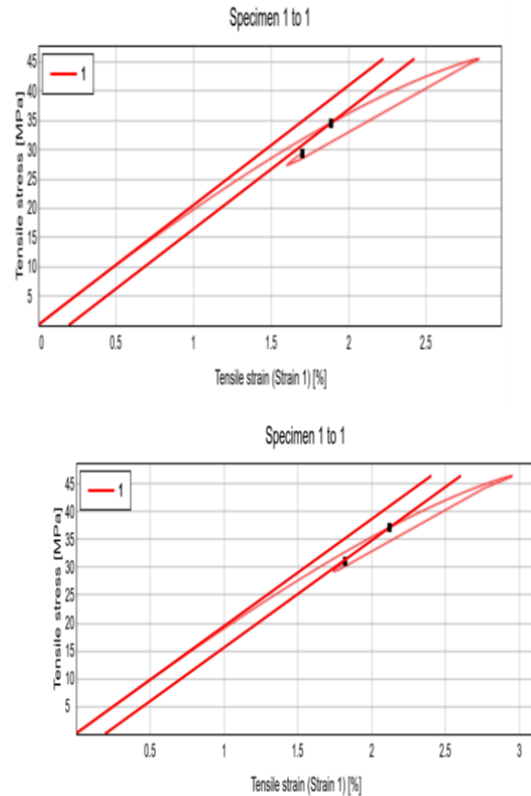
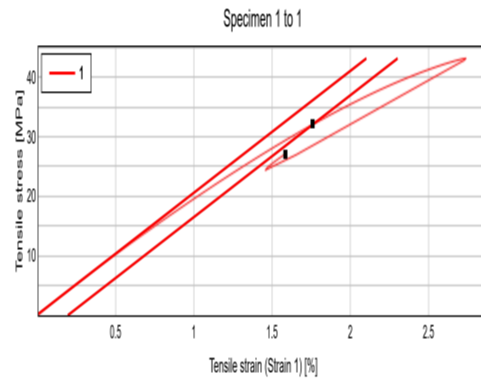


Fig. 9. Specific stress-strain curve for samples 1 and 2



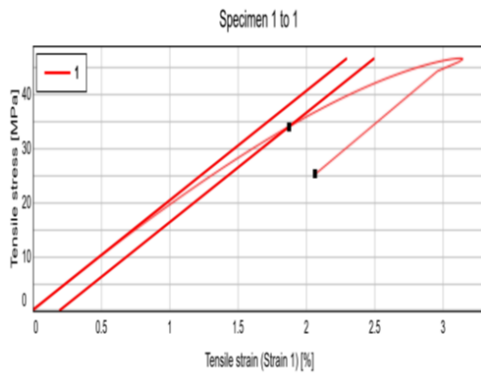


Fig. 10. Specific stress-strain curve for samples 3 and 4

From the specific curves, the following aspects can be observed:

- In the first part, a linear zone is indeed noticed, the slope of which constitutes the longitudinal modulus of elasticity;

- When the stress reaches a value of approx. 20 MPa and the longitudinal specific deformation of approx. 1%, a curvature of the variation graph is observed, signifying the transition to the plastic range of the material;

- The breaking moment occurs at stress values of approximately 45 MPa and longitudinal specific deformation of 3%;

- The maximum value of the longitudinal specific deformation is small (3%), which shows the brittle nature of this material. Moreover, since leaving the elastic range, the samples no longer accumulate too much plastic deformation energy, as will be seen in table 1.

Table 1. Values obtained by tensile testing of sample 1

Modulus (Automatic Young's) [MPa]	Tensile stress at Yield (Offset 0.2 %) [MPa]	Tensile strain (Strain 1) at Yield (Offset 0.2 %) [%]
2042.89	34.64	1.89
Force at Yield (Offset 0.2 %) [kN]	Displacement at Yield (Offset 0.2 %) [mm]	Energy at Yield (Offset 0.2 %) [J]
0.55	2.01	0.07
Status number at Yield (Offset 0.2 %)	Force at Break (Standard) [kN]	Tensile strain (Strain 1) at Maximum Force [%]
1	0.47	2.83
Tensile stress at Maximum Force [MPa]	Tensile displacement at Break (Standard) [mm]	Displacement at Maximum Force [mm]
45.58	0.21	3.09
Maximum Force [kN]	Tensile stress at Break (Standard) [MPa]	Tensile displacement at Maximum Force [mm]
0.73	29.49	0.35
Status number at Maximum Force	Energy at Break (Standard) [J]	Status number at Break (Standard)
1	0.06	1
Displacement at Break (Standard) [mm]	Tensile strain (Strain 1) at Break (Standard) [%]	Tensile strain (Strain 1) gauge length [mm]
3.46	1.70	12.50

In figure 11, for sample 1, the longitudinal specific stress-strain variation is presented in which the values for elongation Δl are taken from the testing machine based on the machine displacement transducer and 10 is considered to be 58 mm, respectively the length of the calibrated portion of the sample. From figure 11, it is found that the specific deformation of the sample (the 58 mm) reaches 5.32% at maximum stress while the elongation at maximum stress is 3.09 mm (see table 1). If the elongation of the 12.5 mm area, on which the extensometer is mounted, at maximum deformation is calculated, this will be:

$$\Delta l = l_0 \cdot \epsilon = 12,5 \cdot 2,84 / 100 = 0,355 \text{ mm}$$

It is found that the total elongation of the sample is much greater than the elongation of the area on which the extensometer was mounted.

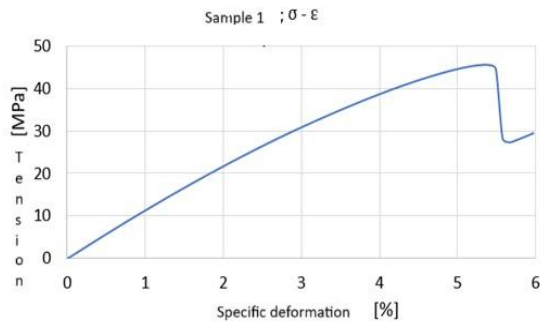


Fig. 11. Stress-strain curve with elongation from the testing machine

In figure 12 we can see the stress-strain curves for the four samples cut from the 0.8 mm discs. No significant differences are found either in the shape of the curves or in the values obtained for the maximum stresses or the maximum longitudinal strains.

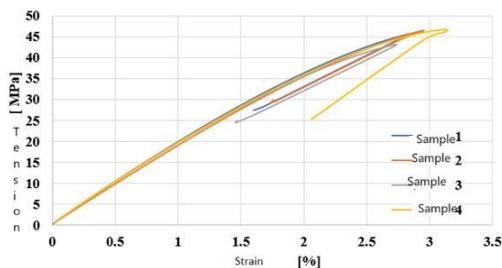


Fig. 12. Superimposed stress-strain curves for samples 1, 2, 3 and 4

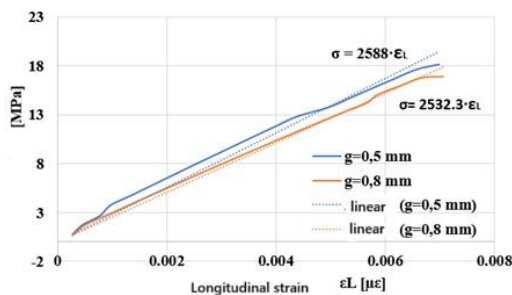


Fig. 13. Longitudinal stress-strain variation curves for samples with marks

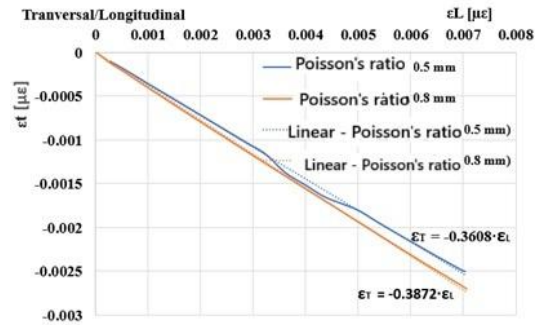


Fig. 14. Specific transverse strain - specific longitudinal strain curve for samples with marks

Figure 13, shows the variations of stress in relation to the longitudinal specific deformation (taken from the longitudinal strain gauge marks), obtained by monoaxial tensile stress in the elastic domain. It is found that the slopes of the two approximation lines have close values, the two values constituting the longitudinal elasticity models for the two types of materials/samples.

Figure 14, shows the variations of the specific transverse strains in relation to the specific longitudinal strain (both taken from the respective strain gauge marks), obtained by monoaxial tensile stress in the elastic domain. It is found that the slopes of the two approximation lines have close values, the two values constituting the Poisson's ratios for the two types of materials/samples.

Lombardo and co-authors [12] examined the mechanical characteristics and investigated the stress relaxation of four different types of aligner materials, two single-layer materials based on PETG and polyurethane and two multilayer materials.

Thermoplastic materials in general follow Hooke's law when subjected to forces of short duration, indicating that within the elastic limit of the stress-strain curve, when the stress is proportional to strain; the material exhibits an elastic behaviour with a return to its original size and shape on the removal of applied stress [13].

The ultimate tensile strength is indicated by the stress at which the material ruptures and the toughness of the material is defined as the energy absorbed by the material before it ruptures, which can be calculated by the area under the stress-strain curve. Thermoplastic materials with higher yield strength, higher ultimate tensile strength and higher toughness are desirable for the fabrication of clear aligners. [14]

An aligner material should ideally possess adequate stiffness to exert the forces and moments needed to achieve the planned tooth movement. If the material used for aligner fabrication exhibits a very high modulus of elasticity (or high stiffness), then the resultant aligner would be very stiff leading to difficulty in aligner placement and removal for the patient. Likewise, a material with low stiffness will not be able to generate adequate forces required to move teeth [13].

The aligners' material properties and the strength of the applied force both affect this relaxation. With transparent aligners, force decreases exponentially rather than linearly over time, with a notable decrease in force occurring during the first few hours of use, which is suggestive of material fatigue [15]. Two single-layer materials based on PETG and polyurethane, two multi-layer materials, and two single-layer materials were the subjects of a study by Lombardo and colleagues [15] on the mechanical properties and stress relaxation of aligner materials. According to their research, multi-layer

materials had consistent stress relaxation and absolute stress resistance that was four times lower than that of single-layer materials, whereas single-layer materials shown significant resistance to absolute stress and quick stress relaxation. In orthodontics, biomaterials must meet specific requirements related to biocompatibility, corrosion resistance and the ability to withstand long-term mechanical forces. [16, 17]

CONCLUSIONS

1. When the stress reaches a value of approx. 20 MPa and the longitudinal specific deformation of approx. 1%, is observed a curvature of the variation graph, signifying the transition to the plastic range of the material, and the breaking moment occurs at stress values of approximately 45 MPa, longitudinal specific deformation of 3% which shows the brittle nature of the material.
2. There were no significant differences founded either in the shape of the curves or in the values obtained for the maximum stresses or the maximum longitudinal strains.
3. The variations of stress in relation to the longitudinal and transversal specific deformation revealed that the slopes of the two approximation lines have close values, the two values constituting the Poisson's ratios for the two types of materials/samples.

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