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MECHANICAL PROPERTIES OF THE MATERIALS FOR BRUXOGUARDS

MEHANSKE LASTNOSTI MATERIALOV ZA NOČNE ZOBNE ŠČITNIKE

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The aim of this study is to investigate the mechanical properties of polymethyl methacrylate (PMMA) and thermoplastic polycarbonate (TPC) materials in order to produce night bruxoguards. For this purpose we used a static tensile test. In the next step the microstructures of PMMA and TPC were observed. Within this framework special attention was paid to the examination of the tensile-test tube fracture surfaces for both materials. This approach revealed that PMMA is a brittle and TPC is a plastic material. Certain mechanical properties and a review of the crucial areas confirmed that the TPC material is extremely favourable for making occlusal splints.

Keywords: bruxoguards, polymethyl methacrylate (PMMA), thermoplastic polycarbonate (TPC), mechanical properties, characterization

Namen te študije je preiskava mehanskih lastnosti polimetil metakrilata (PMMA) in termoplastičnega polikarbonata (TPC) za izdelavo nočnih zobnih ščitnikov. Za ta namen je bil uporabljen statični natezni preizkus. V naslednjem koraku je bila preiskana mikrostruktura PMMA in TPC. Posebna pozornost je bila namenjena preiskavi površine preloma na ceveh za natezni preizkus, izdelanih iz obeh materialov. Tako je bilo ugotovljeno, da je PMMA krhek material, TPC pa plastičen. Nekatere mehanske lastnosti in pregled ključnih področij potrjujejo, da je za izdelavo okluzalne opornice izredno primeren material TPC.

Ključne besede: nočni zobni ščitnik, polimetil metakrilat (PMMA), termoplastični polikarbonat (TPC), mehanske lastnosti, karakterizacija

1 INTRODUCTION

Sleep bruxism (SB) is associated with a rhythmic masticatory muscle activity, characterized by repetitive jaw-muscle contractions, occurring during sleep in the NREM stage.[1] Sleep bruxism is reported by 4.4–8.0 % of the adult population, 14 % of children and is regulated mainly centrally, not peripherally. In terms of etiology, stress and psychosocial variables have been associated with SB. The strongest agreement among several authors is that SB patients are anxious personalities (but not having an anxiety disorder) and are more task-oriented (e.g., focused on a successful performance) in comparison with others.[2] During nocturnal bruxism, the bite forces are much greater than those exerted during mastication. The mean maximum bite force among Europeans and Americans is in the range of 600–750 N, while masticatory forces are much lower (about 60–100 N). During clenching, the forces of about 1000–1500 N, or higher, have been reported. In some individuals, the forces generated and the duration of repeated bruxing episodes can produce considerable loads which are potentially harmful for all the components of the orofacial system.[3,4] The consequences of SB may include tooth destruction, implant fracture, jaw pain, headaches or a limitation of mandibular movement, as well as tooth-grinding sounds that disrupt the sleep of bed partners.[5] Sleep bruxism alone, as long as it is performed subconsciously by the patient and no apparent damage to the oral structure is caused, does not require any therapy. In the case of damage, a multitude of therapeutic approaches is possible, such as drugs (benzodiazepine, tricyclic antidepressants), occlusal adjustment, bruxoguards (occlusal splints) or even occlusal rehabilitation and anti-stress therapy (biofeedback and self-awareness).[6]

Occlusal splints have been advocated to reduce the harmful consequences of bruxism[7], especially when the goal is to protect large restorations and implants. Splints may reduce the total amount of nocturnal activity of bruxers by decreasing the number of bruxing events per night and may also reduce daytime postural muscle activity.[8] However; it is not actually known whether splints can absorb some of the stresses transmitted to the teeth. There is no universal agreement as to the effect of hard and soft splints on bruxism.[9] It was reported that hard stabilization splints decrease muscle activity significantly[10], while the vacuum-formed soft splints increase muscle activity.[11,12]

The aim of this study was to investigate the mechanical properties of two different, most commonly used materials, hard polymethyl methacrylate (PMMA) and thermoplastic polycarbonate (TPC), with respect to using them for the production of customized bruxoguards. In this way we wanted to provide an explanation of the plastic-elastic behaviour of SB materials which could be a guideline for dentists when choosing the correct bruxoguard material. PMMA is possibly more widely known as acrylic is a superb optical material with high levels of both visible and UV light transmission. It is often used for a multitude of point-of-sale display applications and, due to its compatibility with human tissue, it has found use in a number of medical applications. The characteristics of PMMA include low density, excellent light transmission, good electrical properties and compatibility with human tissue (medical grades). TPC is a type of thermoplastics that features polymers linked together by carbonate groups, forming a long molecular chain. TPC is similar to PMMA, but TPC is stronger and has exceptional physical properties and it is usable over a larger temperature range. The advantages of TPC include impact resistance, dielectric strength, excellent formability, superior optical clarity, outstanding dimensional stability, UV stabilization, etc.

2 EXPERIMENTAL WORK

PMMA and TPC testing probes were produced from plates of 2 mm – the optimum guard thickness. The PMMA material was made in Galenika (Serbia) by a dental technician from a heat-curing acrylic resin (**Figure 1a**). PMMA is a strong and lightweight material. It has a density of 1170–1200 kg/m^3, which is less than half that of glass. It also has good impact strength, higher than both glass and polystyrene; however, PMMA's impact strength is still significantly lower than those of polycarbonate and some engineered polymers. PMMA ignites at 460 °C and burns, forming carbon dioxide, water, carbon monoxide and low-molecular-mass compounds, including formaldehyde. PMMA transmits up to 92 % of visible light (a thickness 3 mm) and gives a reflection of about 4 % from each of its surfaces on account of its refractive index (1.4914 at 587.6 nm). It filters ultraviolet (UV) light at the wavelengths below about 300 nm (similar to ordinary window glass).[13,14]

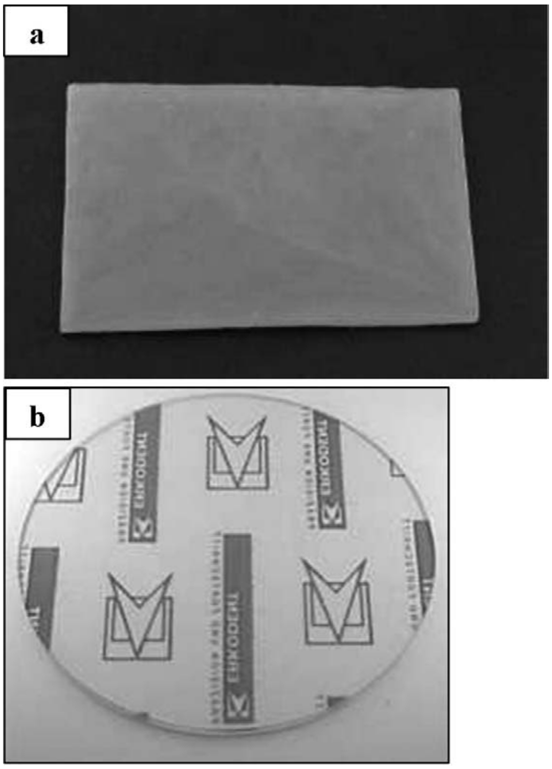

Figure 1: a) PMMA plate (Galenika, Serbia) and b) TPC plate (Erkodent, Germany)

Slika 1: a) Plošča iz PMMA (Galenika, Srbija) in b) plošča iz TPC (Erkodent, Nemčija)

The TPC material was produced by Erkodent (Germany) (**Figure 1b**) and it is composed of PETG: polyethylene terephthalate-glycol-modified ethylene-1.4-cyclohexylene dimethylene terephthalate copolymer. PETG is a thermoplastic polymer that turns into liquid when heated and its hardness is very near the glassy state when cooled. TPC is highly impact resistant, exhibiting excellent clarity and having the density of 1380 kg/m^3 (at 20 °C).[15]

All the prepared samples were subjected to several tests to investigate their mechanical properties, using the following methodology: the static tensile test on a universal testing machine (Zwick/Roell ZO 10). For each material the measurements were done in a series that consisted of six samples in the form of a tensile-test specimen. The standard dimensions of a tensile-test specimen are shown in **Figure 2**. Experimental settings and conditions, shape and dimensions of the tension specimens were in accordance with standard SIST EN 1562:2000 (chapter 6.2). The task was to apply a static tensile load in order to measure the magnitude of the strain at the moment of fracture of an individual tensile specimen. The measurements were conducted at a constant strain-rate increase, which amounted to v = 1.5 mm/min. This speed was selected on the basis of the

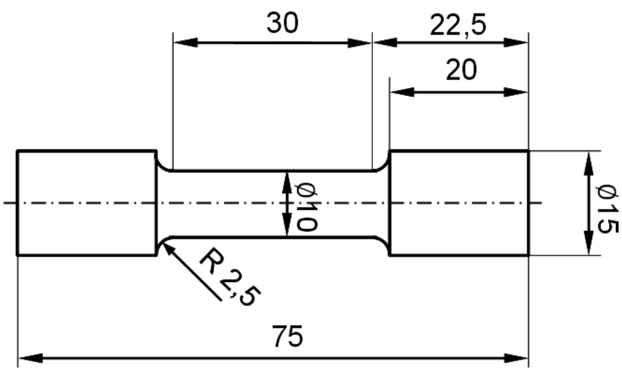

Figure 2: Schematic presentation of a standard tensile-test specimen with dimensions

Slika 2: Shematski prikaz in dimenzije standardnega vzorca za natezni preizkus theory of viscoelastic behaviour, which enabled the chain slip and plastic deformation of both materials. The following parameters were determined by analysing the measured values: yield point (stress) $R_{p0.2}$, ultimate tensile strength R_m and elongation at break of tensile specimen A.

The aim of this part of the investigation was to obtain the real data for the mechanical properties of the PMMA and TPC materials which are generally not known. In this manner we want to predict a possible use of these materials in the special field of dentistry (SB).

The examination of the microstructures of the PMMA and TPC plates included observations of the cross-sections of both materials and a qualitative micro-chemical analysis carried out at the characteristic points or stages. The samples were cleaned with an ultrasonic vibration instrument for cleaning where the medium was alcohol. The cleaned samples were mounted into a special holder, which was placed in the chamber of an electron microscope, Sirion NC 400.

We also observed the surfaces of the broken tensile-test tubes with a scanning electron microscope, Quanta 200 3D, which features a dual-beam system – electronic and ionic (a dual beam). The samples were observed at low vacuum, which allowed an observation of the conductive and non-conductive samples without a prior preparation. Through a review of the fractured surfaces, we wanted to determine the type of fracture and, in this way, the behaviour of the materials during the operation of occlusal forces during nocturnal bruxism that had surpassed the maximum desired biting force by almost 30–60 %.

An XRD analysis was performed on the PMMA and TPC materials. Diffractograms were recorded on a PANalyticalX'pert PRO MPD diffractometer using the reflection technique with the Cu $K_{\alpha 1}$ radiation in the range of 30° to 120° 2θ. The diffractograms were compared with ProgrammeX'pertHighScore (PANalytical) (ICDD, 2006, ICSD, 2007).

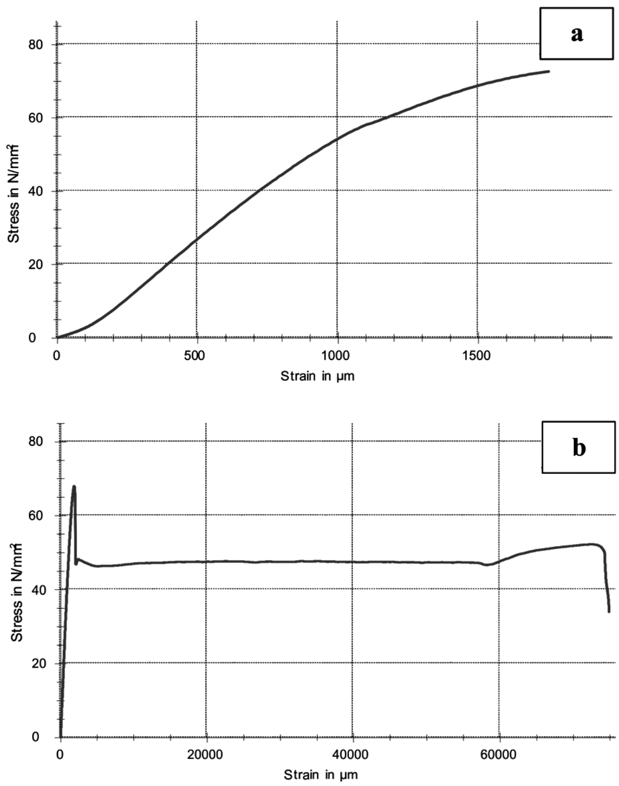

Figure 3: Typical σ – ε curves: a) for PMMA and b) for TPC
Slika 3: Značilna krivulja σ – ε: a) PMMA in b) TPC

3 RESULTS AND DISCUSSION

The results of the mechanical-property measurement were shown in a graphical form with the typical σ – ε curve for the PMMA material (**Figure 3a**). The curve describes the flow of the changes in the voltage dependence of the measured deformation of the sample.

On the a-axis in all the diagrams the tension was marked in MPa, and on the ordinate axis the strain of the sample was in µm. From the σ – ε curves and from the results given in **Table 1**, it can be concluded that these PMMA polymers have a pretty high modulus of elasticity; they were broken in a non-linear elastic range, but the stretch in the elastic field reached only a few percent (1.05 %). It can be seen that the tensile strength is 72.65 MPa and the measured elongation is 1.85 mm, which means that the elongation at the break is A = 2.48 %. The average value of the measured elastic module for PMMA is 2.04 GPa.

Table 1: Average values of (measured) mechanical properties for PMMA and TPC materials
Tabela 1: Srednje vrednosti (izmerjenih) mehanskih lastnosti materialov PMMA in TPC

Material	Engineering stress σ/MPa	Young's modulus E/GPa	Ultimate tensile strength R_m/MPa	Fracture strain ε/mm
PMMA	5.21	2.04	72.65	1.85
TPC	4.15	1.94	67.97	74.86

Figure 3b shows a typical σ – ε curve for the TPC material, from which the material creep was clearly observed. The average values of the results from the tensile tests for the TPC material are given in the second line of **Table 1**. Here the value for the tensile strength is 67.97

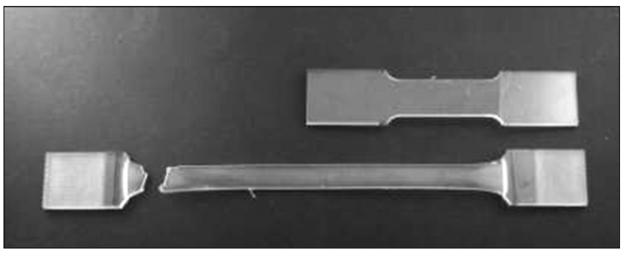
Figure 4: Elongation of the TPC tensile specimens before tensile testing and after the break
Slika 4: Natezni preizkušanec iz TPC pred preizkusom in po porušitvi

MPa which is lower than that of PMMA. However, the measured elongation is 74.86 mm, which makes the value of elongation at break to be A = 99.81 %. The average value of the elastic module is 1.94 GPa. From the typical curves, and based on the average of the measured results of the mechanical tests for the TPC material, it can be concluded that this material has a lower modulus of elasticity and tensile strength than the PMMA material, but its stretching ability is almost a hundred times greater. Greater stretching is clearly seen in **Figure 4**, where parallel tensile TPC specimens are shown – the tensile specimen before and after the break. At the beginning of TPC the material deformation was elastic, and then there was distinct tension strength, ending the tension. The consolidating factor in the plastic region was small and cracking occurred when the stress exceeded the cohesion strength. It should be noted that the TPC material in the sphere of sliding was, on average, loaded for 45 min before the fracture of the tensile specimen took place.

Figure 5a shows a SEM microstructure of PMMA without crystal grains and this means that the material belongs to the amorphous group. A detailed examination showed that within the volume there are micropores with a size of less than 1 µm. In a detailed review of the PMMA structure the presence of the particles with the size of a few µm was identified. Most of the particles were round and had a non-homogeneous distribution within the volume. The results of the qualitative analysis of these particles were confirmed with the increased amounts of chlorine (Cl), potassium (K) and sulphur (S) – this data is not shown. The review of the PMMA material's surface showed an inhomogeneity of the structure, which reflected a high degree of roughness.

A SEM microstructure of the TPC material can be seen in **Figure 5b**, showing typical characteristics of the amorphous state. The observations and studies demonstrated that this material is quite homogeneous, with some lamellar structure and with almost no defects. No other inclusions or faults were observed.

By inspecting the fracture surface of the PMMA material it was found that it had the typical characteristics of a brittle fracture. The lines of sliding, the so-called "rivers", were also present in the figure with a lower magnification (**Figure 6a**) and, normally, in the microstructure of the PMMA samples with a higher magnification (**Figure 6b**). The resulting "rivers" were about 10 µm in length and extended at right angles in the direction of the load. Brittle materials did not deform plastically under the mechanical loading; therefore, the fracture strain was extremely reduced at the eventual fracture. As some particles were found in this material, they are probably one of reasons responsible for the brittleness. Namely, the particles acted as obstacles to plastic deformation leading to a higher value of the elastic modulus and tensile strength, which means that some kind of strengthening effect is achieved in PMMA. As a consequence, at the top of the fracture a concentration of stress was detected because the progression of the fracture was not necessary to achieve the cohesive strength along the entire cross-section of the sample but on both its surfaces. When, in the brittle material, the fracture began to move forward, it was going to break and reduce the external loading. This phenomenon makes the use of the PMMA material for splints extre-

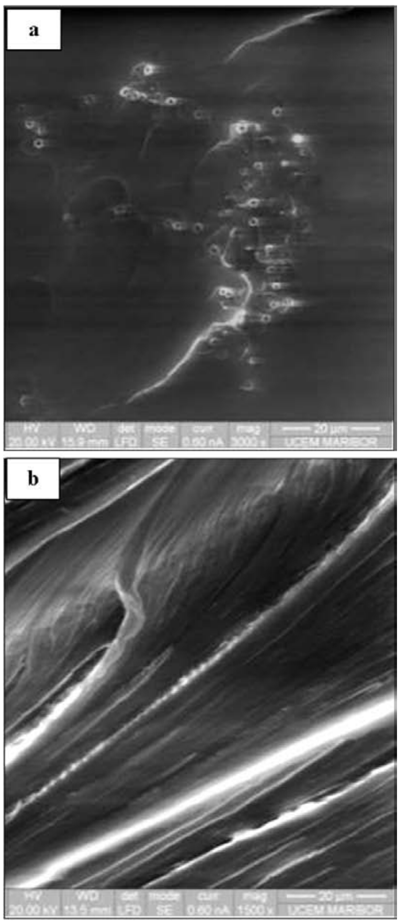

Figure 5: Electron micrographs of: a) PMMA and b) TPC
Slika 5: SEM-posnetka: a) PMMA in b) TPC

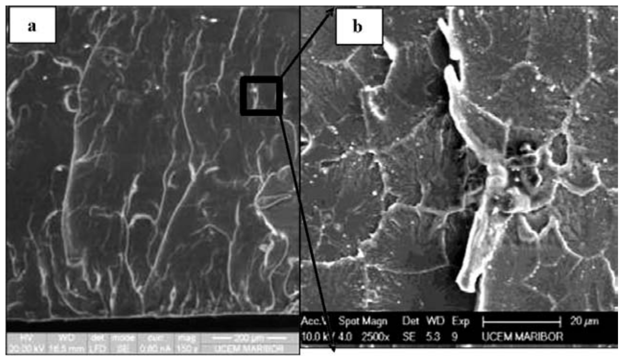

Figure 6: Electron micrographs of the PMMA fracture surface: a) general impression and b) detail
Slika 6: SEM-posnetka površine preloma PMMA: a) videz in b) detajl

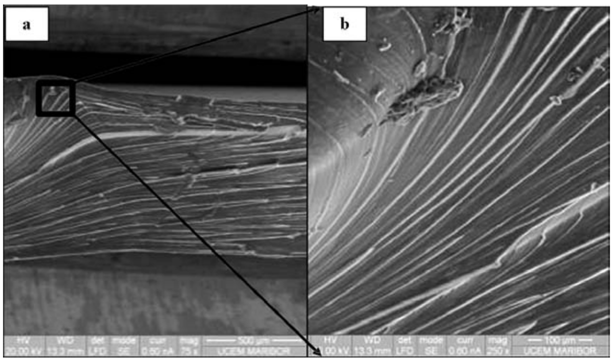

Figure 7: Electron micrographs of the TPC fracture surface: a) general impression and b) detail
Slika 7: SEM-posnetka površine preloma TPC: a) videz in b) detajl

mely unfavourable. Based on the investigations of the structure of the fractured surface of the PMMA material, we can hypothesize that only on the lower part was there a certain degree of plastic deformation.

For the TPC material, the inspection of the fracture surfaces revealed that it behaves elastically (**Figure 7a**).[16] In the structure of the entire intersection sliding lines are present, that is "rivers", which originate from the area where the shooting material continues to spread like feathers on its turning over the entire surface (**Figure 7b**). The sliding lines are at an angle of 45° relative to the direction of the loading during the tensile test, in the direction of the action of the shear stress. A proper selection of technological parameters (the power of prestress, the strain rate) caused a sliding of the chains and a large plastic deformation. Due to a low strain rate the polymer chains had the time to slide next to each other. In the $\sigma - \varepsilon$ diagram it was observed that in a relatively short time of the tensile loading in the TPC material there was a drop in the stress from 75 MPa to 55 MPa, which was a constant all the time during the sliding to the fracture of the material. The cause can be found in the stress relaxation. At the beginning the defined stress in the polymer was necessary in order to achieve a deformation. As the polymer chains flowed viscously into each other, the stress in the polymer material was not preserved. As a result, a decrease in the stress was observed in the $\sigma - \varepsilon$ diagram. This phenomenon can be attributed to the viscous behaviour of the polymer. During the sliding of the TPC polymers there was no consolidation of the materials, except just before the fracture completion, when the stress was increased again to 50 MPa. Certain mechanical characteristics and the inspection of the fracture surfaces confirmed that the usage of the TPC material for splints was favourable.

The results of the XRD analysis indicated that the structures of both materials were amorphous, so that the backgrounds obtained at all the spectra were wide (**Figures 8a** and **8b**). The diffractograms of the PMMA and TPC samples were recorded from the lower and upper surfaces because the aim of the analysis was to examine the influence of the polycarbonate-making technology on

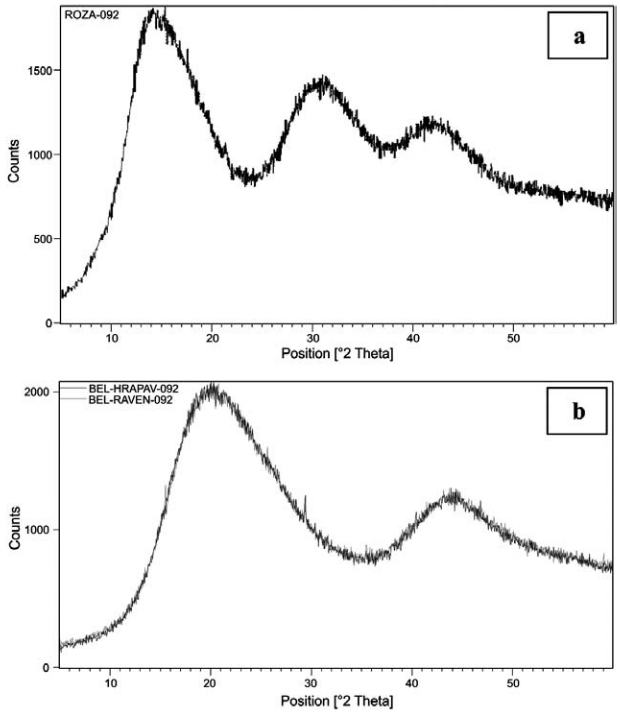

Figure 8: Diffractograms of the samples taken (recorded) from both sides of the plate (rough and smooth) for: a) PMMA and b) TPC
Slika 8: Difraktogram vzorca z obeh površin (hrapave in gladke) pri: a) PMMA in b) TPC

the structure. The obtained diffractograms did not show any deviation in the phase structure in comparison to the surface. It can be concluded that because of different spectra the samples differ one from the other. Indirectly, this was confirmed by, and can be also seen from, the measured mechanical characteristics.

During an application in the mouth cavity, the materials for splints would be exposed to the stresses that should not cause a fracture. However, a certain degree of previously allowed plastic deformation would be possible. Therefore, it would be necessary to know the mechanisms that influence the yield stress as well as the plasticity of the materials. The investigations of the PMMA and TPC materials have shown that they possess the characteristics of elasto-plastic behaviour so, after a certain degree, the elastic deformations partly change into the plastic deformation. A much higher degree of chain sliding and, consequently, a higher plastic deformation, were found in the TPC material. Moreover, the medium value of the TPC elongation during the tensile test was approximately 100 %. Certain mechanical characteristics and the inspection of the fracture surfaces confirmed that the usage of the TPC material for occlusal splints was very favourable.

The use of splints in the treatment of bruxism ensures a reduction in the wearing out of the tooth and leads to a better force distribution in the dental arch supporting the splint.[17] Moreover, a splint increases cognitive awareness and leads to a behavioural modification via a reduction in the muscular activity.[18] With soft splints, there are contact areas with the opposing tooth because of the resilient properties of the material. Therefore, there is a better distribution of the occlusal force, better energy absorption[19] and almost no change in the compliance, which leads to a decreased bending effect on the teeth. In the oral cavity the materials for night guards are exposed to voltages that may not directly cause their tearing, but can cause a degree of deformation to a predetermined allowable value. Certain mechanical properties and an examination of broken surfaces confirmed that the use of the TPC material for occlusal splints is extremely favourable and has clinical advantages.

4 CONCLUSIONS

Investigations of PMMA and TPC materials showed that they have the characteristics of elasto-plastic behaviour. A comparison of the obtained results demonstrated a significantly higher level of the TPC plastic deformation (A = 99.81 %). PMMA has higher $R_{m0.2}$ and E, but these do not guarantee an efficient usage in the SB dentistry.

The elasto-plastic behaviour of TPC was confirmed by detecting many sliding lines in its fracture microstructure. The position of the sliding lines was almost at an angle of 45° relative to the direction of the loading during the tensile test. This finding can be compared to the situation in the mouth where the teeth forces act in similar directions. On this presumption it can be concluded that the TPC material would have good elasto-plastic behaviour also in the oral environment involving higher biting stresses.

Acknowledgements

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