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Finite element analysis of the impact of the properties of dental wedge materials on functional features

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ABSTRACT

Purpose: Defect of the interproximal wall of the tooth is filled with use the shaped matrix and wedge which seals bottom margin during filling. Better fit of the wedge and equalization of the pressure forces on the matrix is achieved by the compliance of the wedge structure through cuts and perforations and the use of silicone materials and unidirectionally expanded polytetrafluoroethylene (ePTFE). The work presents a methodology for model studies of the mechanics of dental wedges in order to evaluate and compare the impact of wedge materials on functional features. The hypothesis of the work was that the mechanical properties of ePTFE determine the effectiveness of the dental wedge.

Design/methodology/approach: Effect of modulus of elasticity and friction coefficient of wedge and matrix materials on the functional features of the wedge was studied on the way Finite Element Analysis (FEA). Simulation included contact sliding between wedge and matrix what was simulated in nonlinear large displacements regime. The sealing evaluation criterion was the pressure distribution between the wedge and matrix below the lower edge of the defect. Displacement values were the criterion for the loss of convexity as a result of matrix deformation.

Findings: The material for the wedge should be characterized by a low coefficient of friction, low elasticity (ensuring high compliance of the wedge) and at the same time the ability to large permanent deformations, which allows for plastic shaping of the matrix from the side of the defect in order to achieve the required wall convexity and the tangent point.

Research limitations/implications: Results show tendency of phenomena in limitation to model simplification of the interdental gap and the ideal adhesion of the matrix to the tooth and linear elasticity of materials.

Practical implications: The material that best meets the requirements is unidirectionally expanded polytetrafluoroethylene, which has one of the lowest coefficients of friction and very high plasticity necessary to shape the matrix from the inside of the cavity.

Originality/value: Methodology of model study and criteria of functional characteristics of dental wedge was presented.

Keywords: Dental wedge material, Friction, Matrix, Filling, Seal, Finite element analysis (FEA), Pressure

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BIOMEDICAL AND DENTAL MATERIALS AND ENGINEERING

1. Introduction

Filling the defects of the interproximal walls of the teeth (the so-called Class 2 according to Black) is difficult due to limited access. The structure of the form of the filled cavity (matrix) must be fixed in the narrow interdental gap (IG). A dental wedge is used for this. The task of the wedge is to stabilize the matrix and separate the teeth through the forces of pushing in the interdental gap. However, the key is not only to fix the matrix, but also to properly fit to the edge of the defect to seal the filling and to obtain the desired shape of the tangent wall. The functional filling should correctly rebuild the convexity of the proximal wall and the contact point [1,2]. The achievement of this effect is influenced by a number of factors, such as the type and thickness of the matrix and the way it is placed in the interdental gap, polymerization shrinkage or subsequent treatment of the restoration made, as well as the shape and stiffness of the wedge used. Translucency may be an additional functional feature of the wedges, which allows the light of the polymerization lamp to reach the gingival margin.

In order to fulfil a complex function, depending on the clinical situation, wedges are proposed that are structurally different in terms of shapes and materials, from the simplest and cheapest wooden wedges to polymer wedges with complex shapes. Composite plastic wedges are intended to ensure better retention in the interdental space, more accurate adhesion of the matrix and reduction of gum traumatization. Currently, plastic and metal anatomical sectional matrices with a shape similar to the shape of a tooth are commonly used.

Better fit of the wedge and equalization of the pressure forces on the matrix is achieved by the compliance of the wedge structure through cuts and perforations and the use of silicone materials. Recently, wedges made of unidirectionally expanded polytetrafluoroethylene (ePTFE) have been used, which have unique properties [3]. ePTFE has low adhesion and non-stick properties, has a smooth surface and excellent sliding properties, is chemically inert and does not absorb liquids. ePTFE exhibits significant formability, including plasticity, which is a key feature when shaping the matrix from the side of the defect. However, the working of dental wedges has not been presented so far. The method of load transfer study in dentistry is numerical simulation, e.g. Finite Element Method (FEA) [4-8], including contact phenomena [9-12]. The work presents a methodology for model studies of the mechanics of dental wedges in order to evaluate and compare the impact of wedge materials on functional features. The hypothesis of the work was that the mechanical properties of ePTFE determine the effectiveness of the dental wedge.

2. Materials and methodology

The interaction of wedges with matrices was studied by means of numerical simulations using the finite element method (FEA). The methodology of simulation studies consisted in examining the effect of wedge and matrix materials as well as various friction coefficients on the functional features of the wedge, for which the degree of sealing of the cavity edge and matrix deformation was assumed. In practice, the anatomical variability of the shapes of the teeth results in a situation of a greater or lesser mismatch between the wedge and the interdental gap, which, during wedging, makes it difficult to obtain a seal while maintaining the shape of the matrix, i.e. obtaining the contact point and the desired wall convexity. The geometric model of the interdental gap was simplified taking into account the peripheral convexity of the tooth, which was not changed vertically. This convexity was considered crucial for the unequivocal model evaluation of functional features and the elimination of the simultaneous overlapping of the influence of additional shapes of the interdental space. A perfect fit and adherence between the matrix and the tooth was assumed. A specific mismatch was introduced between the matrix and the lateral surface of the wedge. Misfit was the smallest at the bottom and increased upwards (Fig. 1 – misfit). The assumed misfit during the wedging simulation resulted in an uneven distribution of pressure on the sealed surface of the matrix below the cavity edge. The evaluation of the wedges' functional features based on the influence of the wedge material properties on the pressure distribution. Investigation included contact sliding between wedge and matrix surfaces what was simulated in nonlinear large displacements regime with contact calculation with augmented Lagrangian multiplier method (Ansys, Inc.). Due to the complexity of the model, the simulation of plasticity of the material was cancelled at this stage.

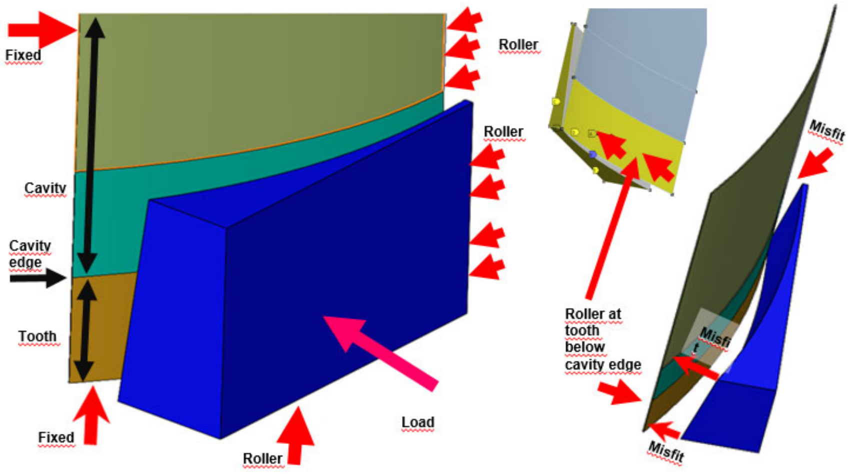

Fig. 1. The wedge and matrix model. Load of the wedge with force of separation. Roller supports at: tooth below cavity, bottom surface of the wedge and middle plane dividing the model in half. Fixed support at matrix vertical and bottom margins

The model was supported by the assumed condition of perfect fit and adherence of the matrix to the tooth. Perfect adherence introduces a fixed support condition along the vertical and bottom edges of the matrix. In fact, the matrix conforms to the tooth depending on the fit of the wedge. In the model, this would require the simulation of additional contact phenomena between the tooth and matrix, which significantly increases the cost of the analysis and often results in difficulties in achieving convergence of the nonlinear analysis. It was assumed that the matrix, due to its much greater compliance as compared to the wedge compliance, will always find a match. Wedge/matrix mismatch was a variable influencing in the model the pressure distribution and the assessed sealing. On the support surface of the matrix below the cavity line, freedom of movement was restricted in the direction normal to the wall being sealed. The freedom of vertical movement was restricted on the lower surface of the wedge (justified by support on the alveolar process). In order to reduce the cost of numerical analysis, the model was divided symmetrically in half in the plane passing through the centre of the interdental space (Fig. 1). A symmetry condition was introduced on the plane of intersection (limitation of movement perpendicular to the plane). This is justified when the maximum insertion force is reached and the wedge is no longer able to slide into space.

The load was the force applied to the middle plane of the wedge, through which the spreading force in the interdental space was simulated as a result of the reaction forces on the surfaces of the adjacent tooth. This force depends on the anatomical shape of the space and the shape of the wedge made of a given material. The wedging forces have not been studied in the literature so far. On the basis of own pilot studies, the measured values of the wedge's pulling force ranged between 10-20 N for the average shape of the space. In the case of wedges pulled with a thread, the maximum value is limited by the thread's load-bearing ability, which is approx. 20 N. The transfer of pulling force to the wedging force (mesial-distal interdental separation) was estimated on the basis of the angular relations for 20 degrees [13] to the maximum value of 3.3 N. The value was taken as the maximum load, and the loads were applied gradually due to the non-linear course of contact phenomena. A similar range of the maximum force of the force value of 7N was recorded in the study of tooth separation forces by pressing the thread into the interdental gap [14]. Also in [13] increase of interdental frictional forces is measurable under values of 3-5 N of distally oriented teeth compression. The gradual loading of the model made it possible to analyse the phenomena occurring while increasing the force depending on the material properties.

The influence of the range of modulus of elasticity of materials that can be used on the wedge for the Young's modulus of elasticity from 2 MPa to 2 GPa was investigated, which in practice corresponds to materials defined as very soft (e.g. silicones) to those characterized by a hardness similar to wood or relatively harder plastics. The simplification of the perfect adhesion of the matrix also allowed to simulate the behaviour of two matrix materials significantly different in elasticity with Young's modulus of 2 GPa or 200 GPa, which corresponds to plastic and steel matrices. The influence of the friction coefficient value in the range from 0.02 through 0.05 to 0.25 between the metal matrix and the wedge in the selected elasticity of 10 MPa and 100 MPa was investigated. In the study of the metal matrix, the load was additionally simulated during the movement of the wedge into the interdental gap, which was carried out by a displacement (drawing the wedge) at the intersection surface of the model in the plane transverse to the gap.

3. Results

The sealing evaluation criterion was the distribution and pressure values between the wedge and matrix below the lower edge of the defect. Displacement values were the criterion for the loss of convexity as a result of matrix deformation. In areas where there was no wedge-to-matrix pressure, for a better overview of the situation, the value of the gap between the wedge and matrix (Gap) in mm was also presented, which shows the lack of ability to fit the wedge to the matrix or in other words "erasing" the assumed wedge/matrix mismatch.

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The following Figures 2-5 show the results of the research on the effect of the wedge stiffness in interaction with the 2 GPa plastic matrix. Figure 2 shows a comparison of the wedge behaviour of a material with 2 GPa and 100 MPa elasticity. The pressure distributions are presented in successive time steps for a better visualization of the behaviour. The stiffer 2 GPa wedge (e.g. wooden, plastic) did not show any conformability. The pressure was negligible in the 1st step of the load and only in the 2nd step was the contact on the lower edge. Finally, in step 3, the pressure was concentrated at the lower edge and was uneven: in the neck and at the end, and increased in the middle. The displacements and clearance values show how much stiffness of the wedge prevents a fit. In Figure 3 at the top edge, in the last time step, the clearance value is 0.3 mm and even in the neck it exceeds 0.1 mm.

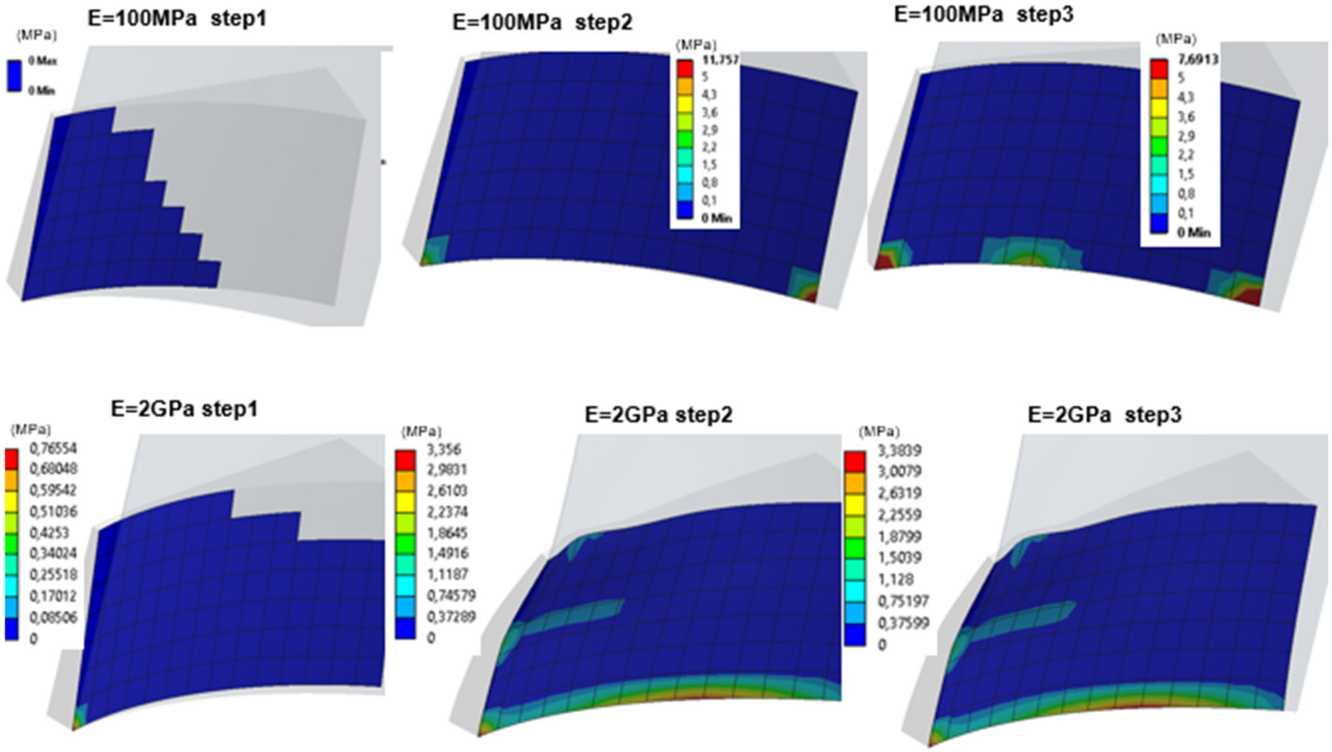

Fig. 2. Comparison of pressure between polymeric matrix and wedge with material with the 2 GPa and 100 MPa modulus of elasticity. The pressure distributions are presented in successive loading time steps for a better visualization of the behaviour

Reducing the stiffness for a wedge with a modulus of elasticity of 100 MPa (hard rubber) significantly affected the sealing. In the last time step, a reduction in the clearance is visible, which, apart from the trailing edge, has been almost completely erased as a result of deformation of the wedge and fitting to the matrix. The distribution of the sealing pressure shows higher values only at the edge of the defect and only in the area of the constriction. The pressure is greatest at the lower edge well below the defect rate as with the stiffest wedge, with a more even distribution along the edge.

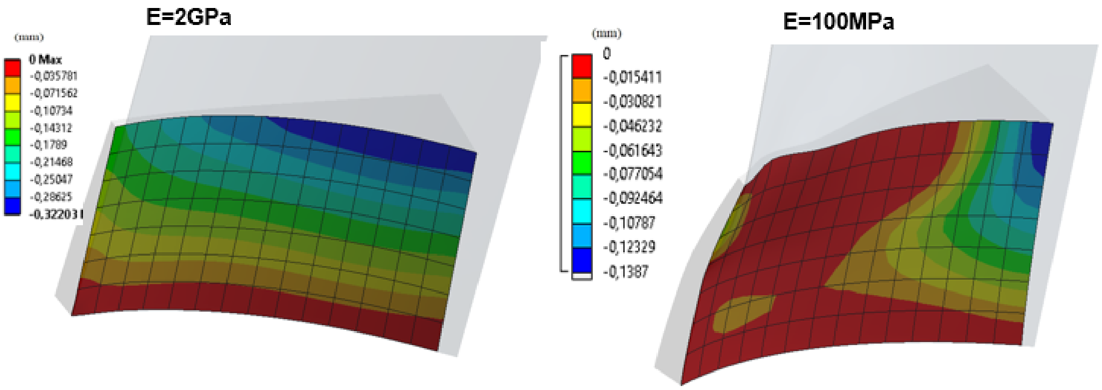

Fig. 3. Comparison of misfit (a gap) in mm between matrix and wedge with material of 2 GPa and 100 MPa modulus of elasticity after the final load

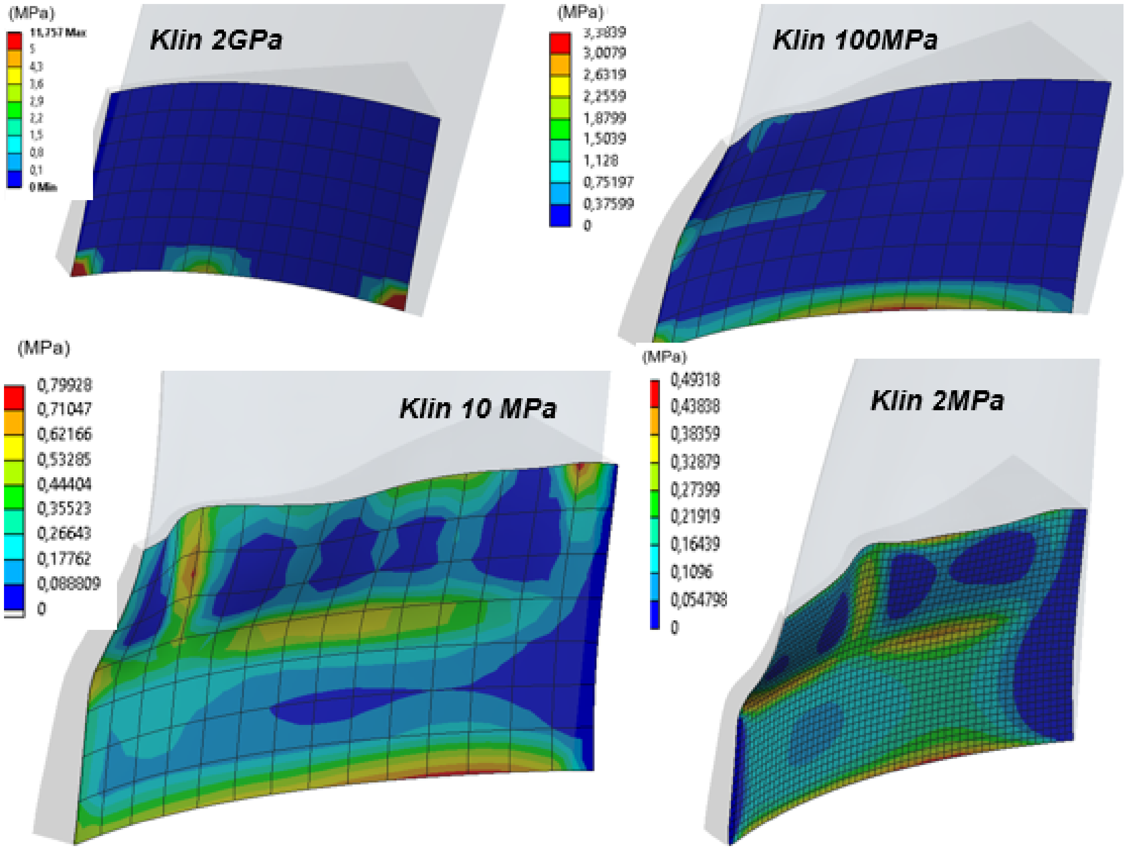

Fig. 4. Pressure between wedge and polymeric matrix dependent on the elasticity of wedge material after the final load

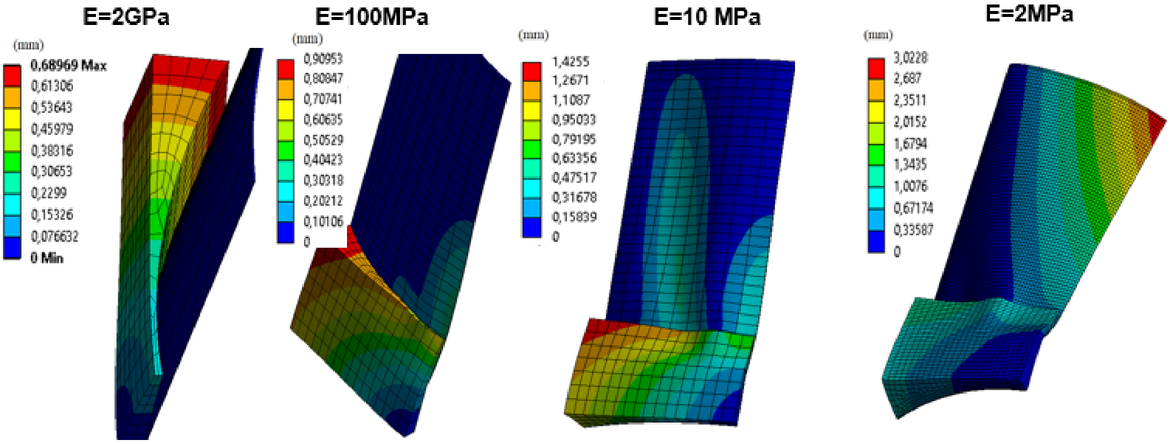

Fig. 5. Wedge and polymeric matrix displacements dependent on the elasticity of wedge material

A significant qualitative change in the sealing occurred only for a wedge with a modulus of 10 MPa (harder silicone), for which the clearance was almost completely erased. At the same time, the pressure along the edge of the defect has reached significant values, reaching 0.5 MPa. However, the pressure distribution on the sealing surface is relatively uneven and disappears at the end of the wedge and is still concentrated at the lower edge.

In the case of a wedge with a modulus of elasticity of 2 MPa, there was further pressure equalization on the sealed wall. Note that adjusting the wedge, however, reduces the pressure at the very edge and equalizes the values on the sealed wall. The model assumes an even distribution of the wedging force on the side surface of the wedge. This assumption resulted from modelling limitations, but at the same time it clearly indicates that the position of the thread plays a significant role, because in the case of a flexible wedge it allows to some extent to direct the force below the edge of the defect, which will result in a more even pressure distribution below the defect and less pressure on the matrix above the defect line.

Nevertheless, with the increase in wedge compliance, a significant increase in matrix deformation was observed. In the case of 2 GPa, the wedge did not press the matrix above the edge of the defect, so it did not deform it. For the 100 MPa wedge, the deflection was 0.3 mm, for the 10 MPa wedge it was 0.6 mm, and for the 2 MPa wedge it was 3 mm. The change of matrix deformation mechanism in the case of the most compliant wedge is noteworthy. Due to the limitations of movement at the edges of the support, the surface was wavy and stiffened in the middle. This tendency was already visible at the 10 MPa wedge. However, the most compliable wedge increased the pressure on the matrix wall above the defect line, which experiences the greatest displacements in the area of the largest neck of the interdental gap. At the same time, along with the increase in the wedge's compliance and the pressure on the matrix, the stresses in the matrix increase, reaching even over 100 MPa. For some matrix materials this may pose a risk of permanent deformation, but in general most polymers exhibit sufficient strength. In practice, before the destruction of the matrix is achieved, it slips out, which leads to the re-preparation of the treatment area with a new matrix. The stresses were not an criterion and were not included in the results.

Figure 6 shows the significant beneficial effect of reducing the coefficient of friction on the value of slip and shear stresses. The maximum value of the slip in the case of the friction coefficient of 0.25 was 0.26 mm in the area of the lower corner of the wedge. The reduction of the friction coefficient to the value of 0.02 resulted in a slight increase in the slip in this area, to a value slightly above 0.3 mm, with the simultaneous favourable equalization of the slip along the lower edge. At the same time, the tangential stresses were reduced by an order of magnitude from 0.16 to 0.014 MPa for the greater friction coefficient of 0.25 and the smallest of 0.02, respectively. The stresses in the matrix in the case of the friction coefficient of 0.02, 0.05 and 0.25 were respectively 88, 90 and 110 MPa (this increase in stress was also omitted in the presentation).

In the case of the metal matrix, due to its stiffness and the greatest resistance to the movement of the wedge, the insertion of the wedge was analysed, while the insertion was analysed with the prior application of pressure by the wedging force in a manner analogous to the previous cases for the polymeric matrix. The pressure distributions in Figure 7 for the wedges with a modulus of elasticity of 100 MPa and 10 MPa confirmed that the wedge with a modulus of 100 MPa is too stiff to conform to the shape of a metal matrix.

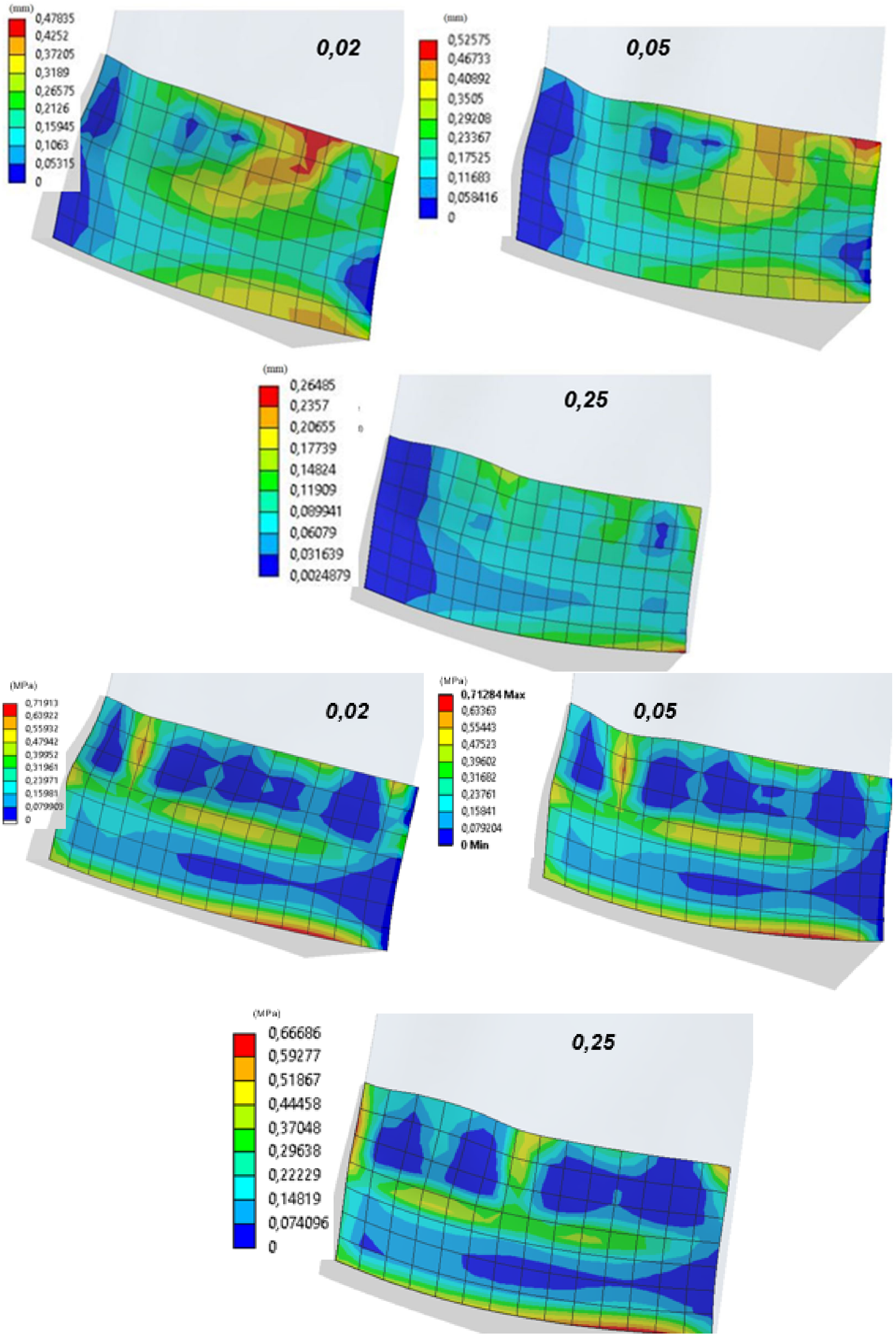

Fig. 6. The influence of the friction coefficient of the wedge material for the value of 0.02; 0.05 and 0.25 for slip (mm) and frictional (tangential) stress (MPa)

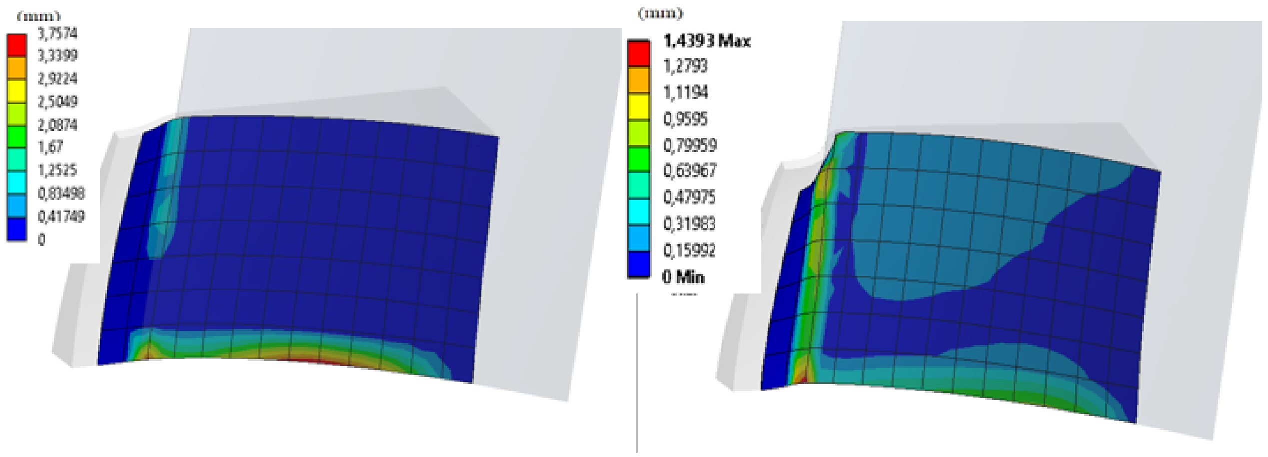

Fig. 7. Pressure between metallic matrix and wedge (of 2 GPa and 100 MPa modulus of elasticity) during insertion into the interdental space

The pressure distribution was similar to that in the case of cooperation with a more compliant plastic matrix (in the area of the support in the gap, there was an artifact of the FEM model from the vertical edge, resulting from model simplifications during wedge insertion, which should not be considered as the result of the analysis). The stresses in the metal matrix did not exceed 250 MPa, which is a considerable margin of load bearing ability, with the simultaneous lack of significant deformations, which was caused by the 100 times greater modulus of elasticity of steel compared to polymers.

It is known from clinical practice that proximal contact is an fundamental factor in maintaining and stabilizing the dental arch and improperly shaped filing causes food impaction, dental caries, periodontal disease, failure of occlusion and an undesirable teeth movement [14-18]. The results are consistent with clinical practice because it is difficult to anatomically fit a wooden or hard plastic wedge and instead of sealing the bottom edge, the pressure on the matrix causes the matrix deformation and loss of convexity (concavity to the cavity). In the case of the metallic matrices it is particularly difficult to achieve anatomical convexity, and excessive plastic deformation usually prevents this completely. A stiff wedge in practice often leads to a loss of tightness due to the matrix moving with it. This is due to the concentration of forces in the areas of contact and the pulling of the matrix while there is play in the areas of mismatch. Increasing the wedging force worsens the situation as the tangential forces are increasing, with the play areas increasing due to the increasing separation of the teeth. This increases the tendency for the matrix to fold and lose its seal or be damaged. In the simulation, due to the model simplification of the ideal adhesion of the matrix to the tooth, only the tendency to this unfavourable phenomenon can be analysed. It has been found a reduction in tangential stress which reduces the tendency of the matrix to be pulled by the inserting wedge. In practice, inserting a stiff wedge results in the loss of adhesion of the matrix to the tooth, which in consequence usually leads to large deformations, including plastic deformations, which avoid proper filling.

It is worth noting a similar effect on the surface of contact with the cofferdam, which was not included in the simulation also due to the simplification. In clinical practice, the phenomenon of cofferdam slipping under tangential stresses generated on the surface of the inserted wedge, especially a wooden wedge, which is characterized by a high coefficient of friction, often occurs. The beneficial reduction of these stresses in contact with the matrix in an analogous manner will be present on the surface of the cofferdam and will reduce the tendency to deformation and sliding.

The results also show that the soft silicone wedges are unable to prevent the disadvantageous effect of losing the convexity and contact point. Although, thanks to their high compliance, they ensure an even seal, due to the lack of plastic properties (silicones show instantaneous or nearly instantaneous deformation), they do not allow the tangential wall to be shaped from the inside of the defect. It should also be emphasized that the more compliant wedge just unfavourably deforms the matrix above the defect threshold. Thus, increasing compliance has a favourable effect on the sealing but disadvantageous in achieving the convexity of the tangential wall. It is therefore necessary to use, for example, an ePTFE exhibiting a high degree of plasticity, which allows the matrix to be shaped.

According to the authors' knowledge, these are the first studies of the functional characteristics and material properties of wedges, which, limited to the simplifications introduced at the present stage of the research, allowed for the analysis of phenomena and tendencies. However, for a more precise representation of the real system, further development of the model is needed.

4. Conclusions

Researches have shown that the stiffness of the wedge for materials with a modulus of elasticity in the range of 2-10 MPa is optimal in terms of sealing the matrix (pressure distribution on the tangent wall below the defect), but at the same time as the stiffness of the wedge is decreased, the deformation of the matrix to the cavity increases to considerable values requiring correction by pushing the matrix from the inside of the defect in order to obtain a tangent point and a convex shape of the wall.

The beneficial effect of reducing the value of the friction coefficient in the range of 0.25 to 0.02 was found to significantly reduce the value of tangential stresses exerted on the matrix by the inserted wedge, which in practice reduces the tendency to protrude and deform the matrix.

Researches have shown that the material for the wedge should be characterized by a low coefficient of friction, low elasticity (ensuring high compliance of the wedge) and at the same time the ability to large permanent deformations, which allows for plastic shaping of the matrix from the side of the defect in order to achieve the required wall convexity and the tangent point.

The material that best meets the requirements is unidirectionally expanded polytetrafluoroethylene, which has one of the lowest coefficients of friction and very high plasticity necessary to shape the matrix from the inside of the cavity.

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