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Phenomenological evaluation of fatigue cracking of dental restorations under conditions of cyclic mechanical loads

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This paper deals with microcracks in dental filling material and hard tissues of the teeth treated conservatively. Human teeth, removed due to orthodontic or surgical reasons, were the subject of those research studies. The studies have been conducted in vitro with the application of mastication simulator. It has been indicated that the number of cracks and the degree of their expansion increase with the number of load cycles. The number of microcracks of the filling material on the masticating surface is lower than in the deeper layers; however, they are more extensive. After applying a specified long load series a progressive increase of microcracks in the restoration material and their expansion in the contact zone with the dentine have been observed. It has been demonstrated that on the masticating surface the number of microcracks and their expansion were proportional to the number of load cycles.

Key words: *cracking, human teeth, in vitro tests*

1. Introduction

1.1. Tooth–filling system structure

Under natural conditions of mechanical loads in the cavity, a biomechanical teeth–composite filling system consists of the filling body and tooth hard tissues, i.e., enamel and dentine (figure 1). Light-cured polymer composites based on the resins are used in the dental treatment. They consist of the matrix (light-cured resin) which makes up approx. 20–40% of the material volume [1], inorganic filling material (ceramic powder based on silica), about 60% of the volume [2], and pre-adhesive agent. The example of the light-cured polymer composite commonly used in the dental practice is ELS, which is also used in this study.

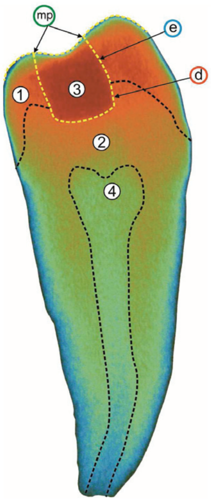

Fig. 1. Tooth with the elements of biomechanical tooth–filling system and the areas observed: 1 – enamel, 2 – dentine, 3 – composite filling; m.p. – masticating surface area, e – enamel area, d – dentine area

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1.2. The reasons for physical-mechanical degradation of the tooth–filling system

A primary cause of the initiation of physical-mechanical degradation process of the tooth–filling system is polymerization shrinkage of the composite filling [3]–[8]. The stress initiated by polymerization shrinkage is responsible for the forces acting in the opposite direction to those adhesive forces that bond tooth tissues and filling material, and result in a marginal leakage of the system. During further use of the filling in the cavity, a mastication process mainly determines its mechanical degradation. Kinematics of mastication process consists in abducent and adducent movements of the lower jaw, as well as lateral movements [9]. Mechanics of the mastication process causes unfavorable conditions of stress in the system structure [10], [11], i.e., in the filling material, enamel and dentine. Long-lasting and cyclic repetition of such conditions lead to decohesion of the system, which appears with the formation of microcracks and the development of the marginal fissure.

1.3. Simulation studies

During a mastication process the tooth with a filling is subject to loading in a very complex condition. Maximum occlusal forces, whose direction is consistent with the direction of the longitudinal axis of the tooth, can be up to 1000 N [12], the contact surface of the opposing teeth is between 0.4 and 2.2 mm^2 [13], and the stresses in such conditions can range from 0.45 to 2.5 GPa [12]. During the mastication process human teeth are additionally loaded with the shear forces, whose vectors run in the horizontal plane and are parallel to the masticating surface. It has been indicated that stresses in the case of the second-class fillings, at the impact of the vertical occlusal force of 400 N, can be up to 500 MPa at the chewing surface, and between 20 and 60 MPa at the filling bottom, at the point of horizontal contact with dentine [14].

In in vitro studies of the process of physical-mechanical degradation of tooth–filling system, equipment simulating physiological conditions in the cavity was used. In the literature, a description of different mastication simulators can be found [15]–[18]. Despite a large number of the studies conducted, up till now there are still many ambiguities about the process of physical-mechanical degradation of tooth–filling system, especially with regards to the mechanisms of formation and expansion of microcracks, as well as their influence on the marginal fissure.

1.4. Objective of the paper

The objective of the studies was to analyze qualitatively and quantitatively fatigue microcracks as one of the main factors of physical-mechanical degradation of the tooth–filling system.

2. Materials and methods

In this study, the extracted human molar and premolar teeth were used, previously removed due to orthodontic and surgical reasons. Tooth specimens were treated as follows. In all specimens, class I model cavity was prepared according to Black's, with the depth of 3 mm, enabling contact with enamel and dentine (figure 2). Our primary aim was to obtain repeatable lesions with their lateral walls perpendicular to the bottoms. The enamel edges of each tooth were smoothened with Arkansas stone. The enamel and dentine were etched with 37% ortho-phosphoric acid. In the following step, the adhesive material was applied to all walls and the bottom of the lesion.

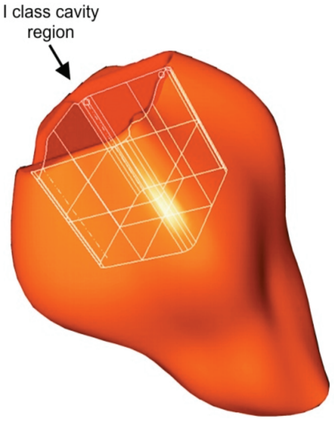

Fig. 2. Scheme of class I cavity according to Black's classification

Composite material fillings were applied to the cavity, according to the manufacturer's recommendations. ELS composite was applied in the layers of 2 mm and cured with halogen lamp for 40 seconds. The specimens were subject to mechanical loads at a special research stand simulating mastication process [19] (figure 3). Cyclic loads with an occlusive force of 400 N were applied according to the scheme presented in

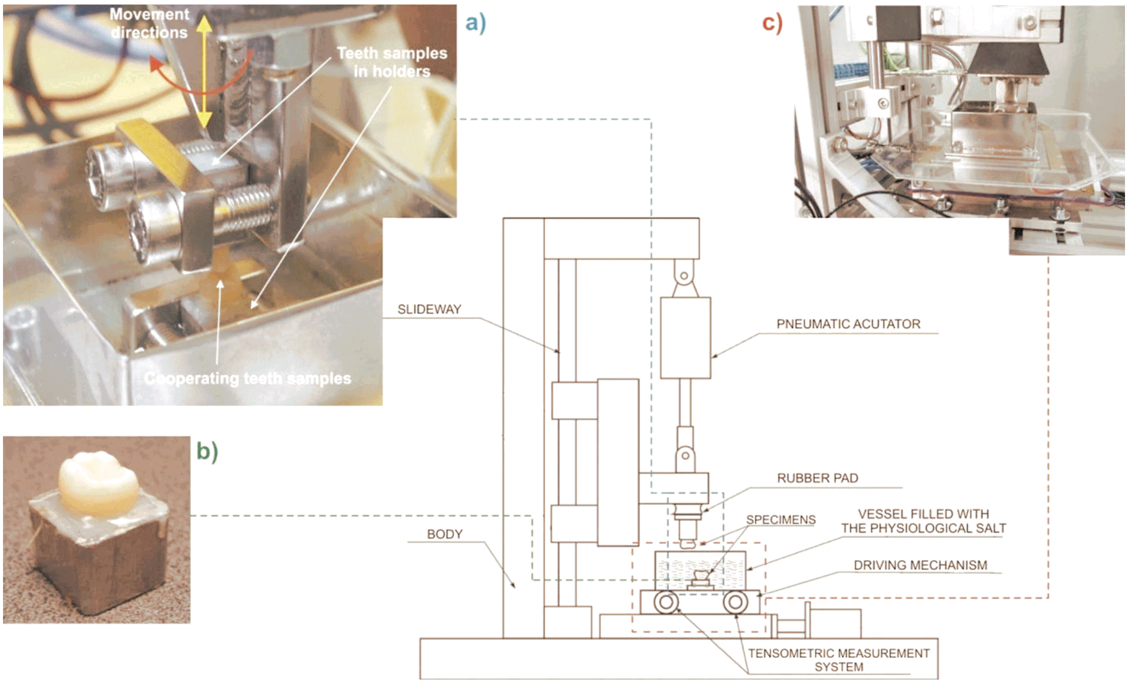

Fig. 3. Mastication simulator: a) cooperating pair of samples, b) sample included in the metal frame, c) mastication simulator plotter

Table. Results of measurement of a number and length of the cracks in the filling material and tooth hard tissues. *MC* stands for a number of load cycles, *N* stands for a number of cracks

MC	*N*	Average	Median	Min	Max	Standard deviation	Coef. of variation [%]
		$m \cdot 10^{-6}$					
Chewing surface area (m.p.)							
0	7	380.43	355.02	81.56	842.37	248.96	65.44
30000	19	223.08	152.91	60.59	465.00	128.49	57.60
60000	35	275.06	179.38	28.87	743.83	205.93	74.87
100000	37	783.11	558.50	19.90	3569.59	727.34	92.88
Enamel area (e)							
0	30	208.38	155.69	30.05	655.62	161.31	77.41
30000	52	185.87	145.86	25.51	450.43	123.52	66.45
60000	77	330.27	288.59	34.12	949.17	217.12	65.74
100000	65	445.11	333.14	34.64	1049.86	270.96	60.87
Dentine area (d)							
0	18	139.41	109.18	16.33	376.51	92.42	66.29
30000	11	196.87	186.77	43.40	411.73	129.19	65.62
60000	34	281.79	228.25	17.20	687.97	208.76	74.08
100000	100	505.93	453.56	60.01	1057.50	261.48	51.68

figure 3a. Mastication trajectory (according to Bates [20]) was applied with the use of computer-controlled plotter. Additionally, lateral forces were measured, being a response of interacting kinematic pair to the forced chewing trajectory. Tooth specimens were fixed on special metal holders (figure 3b). In order to represent an elastic setting of the tooth root in the gum, an appropriately selected resin was used. In this way, the elastic amortizing layer around the tooth was formed. A detailed description of the this mastication simulator can be found in [19], [21].

A fatigue cracking was evaluated based on the microscopic examinations. The cracks on the masticating surface were viewed under SEM (LEO 1430 VP) microscope. For the evaluation of cracks in tooth longitudinal section the optical microscope was used. Examinations were carried out in the bright field on the dedicated microsections. To prepare microsections, after each series of cyclic loads, teeth with the filling were included as a whole in the resin, and next they were subject to a four-stage procedure of grinding and polishing (Buehler Beta with Vector head): polishing wheel 320 SiC, polishing wheel UltraPol + 6 μm of diamond suspension, TextMet 1000 + 3 μm of diamond suspension, ChomoMet + 0.05 μm of diamond suspension. The images obtained in microscopic examination were subjected to the computer image analysis (Image-Pro Plus, Media Cybernetics).

3. Results

The table presents crack parameters of composite filling and tooth hard tissues under conditions of cyclic mechanical loads.

4. Discussion

4.1. Qualitative analysis of results

It has been concluded that in most cases cracks are formed in the areas adjacent to the contact surface of tooth and filling, as well as close to the dentine–enamel junction (figures 6a, 7a, 7b). However, many cases of through cracking (scattered cracking) of the filling material due to its structural heterogeneity have been also demonstrated. The pores (gaps) formed during a process of dental filling preparation are considered to be unfavourable (figure 8b), which has also been stressed in the literature [22]. Another disadvantageous factor is a weakened structure of polymer composite at the borders of the layers put by the dentist. In figure 8a, a change of the cracking propagation direction consistent with layer borders can be seen. Branching of the cracks is related to the fact that most probably border area between composite layers has a lower strength than tooth–filling contact zone (figure 8a).

Considering separately the tooth areas studied, it can be concluded that cracking on the masticating surface of the composite is less frequent than in the deeper areas (figure 4). Different degradation symptoms are more common in this area, such as abrasive and adhesive wearing, the latter being favoured by a nature of chewing process – large compressive forces and low movement velocities.

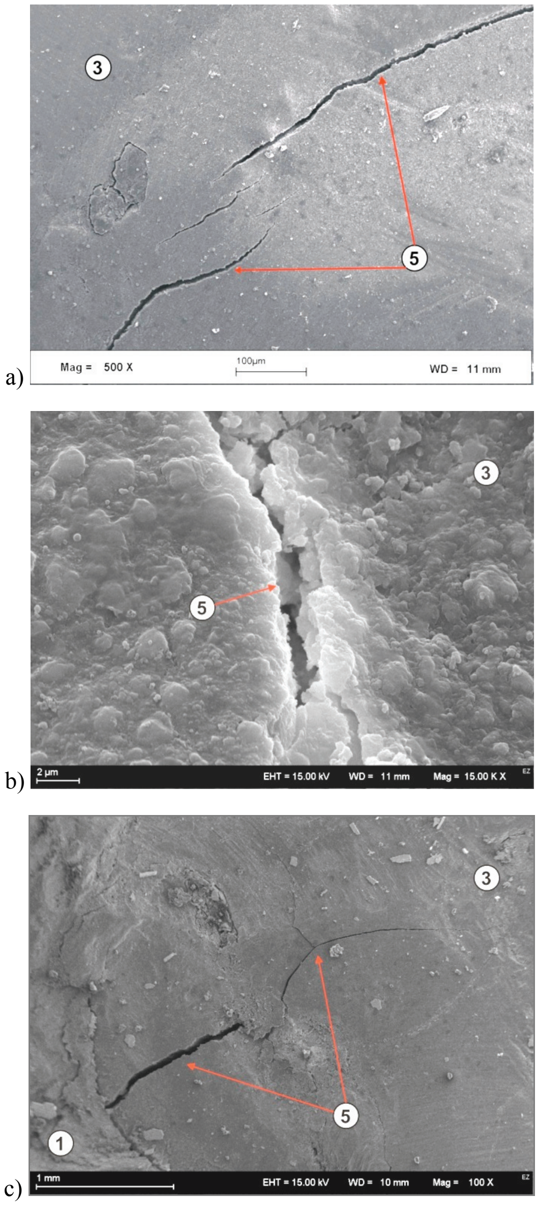

Fig. 4. SEM images of cracking on the masticating surface of the tooth with filling, formed after 100 000 chewing cycles; a) mag. of 500×, b) mag. of 15000×, c) mag. of 100×; 1 – enamel, 3 – filling, 5 – cracking in composite structure

The cracks observed in most cases propagate rectilinearly, between composite particles (figure 4b). Generally, there are not too many branches of the main cracking (figure 4c). Such cracking mechanism has been described in the literature [23]. During the present studies cracks bridging has also been observed (figure 4a), which could have been a result of local increased density of the composite particles.

Figure 5 shows a microscopic image of the part of the filling, visible in the tooth longitudinal section within the area of the masticating surface after 100 000 load cycles. It should be noticed that on the masticating surface (m.p.) there are evident signs of wear. Crack network is dense and rather irregular. The cracks differ from each other in shape, length and propagation direction. Next to the surface of the filling, the direction of cracks is close to perpendicular to the filling surface (a), thus it is consistent with high compressive stresses, appearing at the points of the closest contact at specimens, during fatigue tests. It should also be noted that next to the perpendicular cracks in the places where filling surface is most worn, there are cracks parallel to the masticating surface. Most probably such a direction of propagation is forced by tangent stresses induced by lateral tooth movements. Such a mechanism of degradation can result in fracture of fragments of the filling in the next phases.

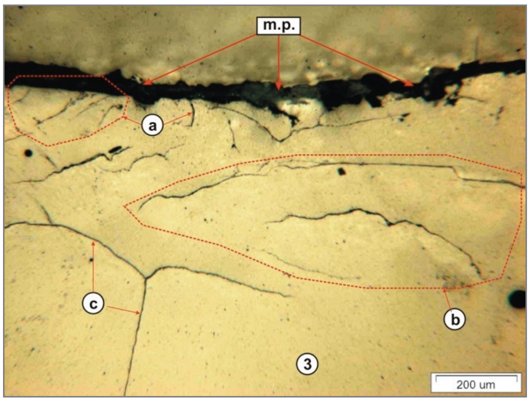

Fig. 5. Microscopic image of longitudinal section of the filling in the masticating surface area after 100 000 load cycles: 3 – filling, m.p. – masticating surface, a – cracks perpendicular to the masticating surface, b – parabolic cracks, c – two-directional cracks

In the image analyzed (figure 5), in the deeper subsurface layers of the filling, the cracks of parabolic shape can be observed. They propagate consistently with the direction of forces tangent to the masticating surface (b). Cracks in this area are less frequent and more complex than the cracks being in the closest proximity to the filling surface. In subsurface zone, a crack propagating in perpendicular direction was also observed (figure 5c). Such cracks were formed most probably as a result of superposition of two parabolic cracks, propagating in the initial phase in the direction close to the direction parallel to the masticating surface.

In figures 6a and 6b, longitudinal sections of the tooth with filling after 60 000 chewing cycles are shown. Within this area a part of contact zone of enamel (1) and composite filling (3) can be seen. Figure 9a depicts a crack at the boundary of enamel and filling (5). The direction of the crack in enamel is consistent with the direction of the tooth–filling contact zone, and its shape is very irregular due to specific enamel structure [24]. Cracking in enamel propagates along the border of hydroxyapatite crystals. A whole macrocrack consists of several microcraks, whose direction is consistent with the direction of macrocrack.

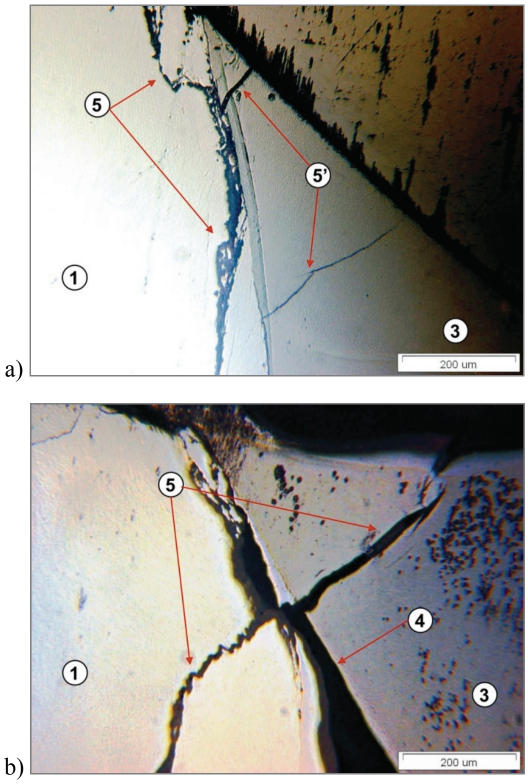

Fig. 6. Microscopic image of the tooth section with composite filling after fatigue tests: a) section in enamel area after 60 000 chewing cycles: 1 – enamel, 3 – filling, 5 – crack in the enamel, 5' – crack of the filling; b) section in enamel area after 60 000 chewing cycles: 1 – enamel, 3 – filling, 4 – marginal leakage, 5 – crack propagating in filling and enamel structures

Cracks visible in figure 6a occur in the composite filling structure (5') and are parallel to each other and perpendicular to the tooth and polymer composite contact zone. These cracks are most probably a result of compressive stresses, acting on a relatively thin composite layer in this area. Figure 6b presents the area of longitudinal tooth section adjacent to the area shown in figure 6a. In this figure, a crack (5) propagates both in the enamel and structure. A crack on the masticating surface propagating from the division border causes the weakening of the composite structure and facture of the whole filling fragment with the expansion of the marginal fissure (4). A shape of the crack in enamel is curvilinear due to its passing through the crystals in enamel structure [25]. Probably a route of propagation of the crack in enamel determines the packing of the inter-crystalline organic layer [26].

Macrocracks are accompanied by tiny microcracks [27]. According to an available literature the dimensions of these microcracks exceed 10 µm [28]. Bajaj and Arola [29] report that they propagate in intercrystalline enamel structure and are the effect of bridging the main crack.

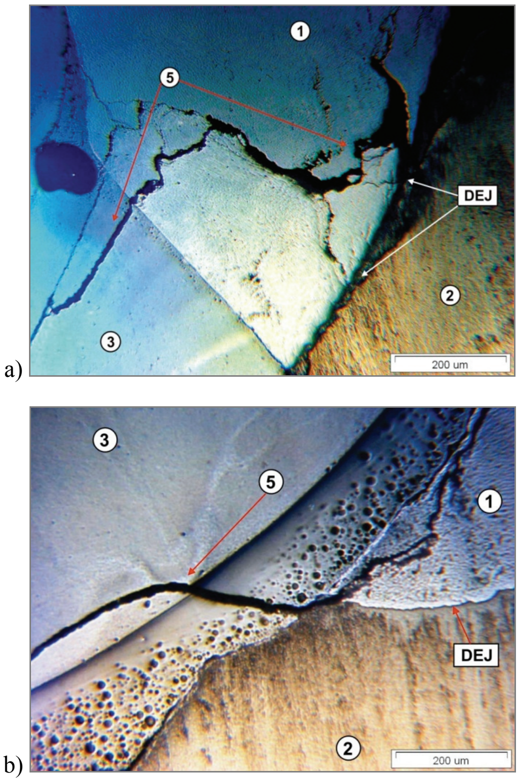

Fig. 7. Microscopic image of the tooth with filling after 100 000 masticating cycles: 1 – enamel, 2 – dentine, 3 – filling, 5 – crack, DEJ – dentine–enamel junction

Irregular way of enamel cracking is also clearly visible in figures 7a and 7b. The cracking of an enamel structure is different from the same cracking of the filling structures (figure 7b). Enamel cracking most probably can be related to the susceptibility to the plastic deformations and elliptical shape of the enamel crystals. Crack initiation takes place at the division surface of enamels crystals [27]. Thus, it seems that the tooth–filling contact surface determines the nature of enamel degradation.

In the case of the contact zone of filling and dentine, most of the cracks occurred in the filling structure (figure 8). In an initial phase, the direction of these cracks was perpendicular to the contact border of dentine and filling. In the consequtive expansion phases, a change of the propagation direction was often observed; it is consistent with the contact border of tooth tissues and filling.

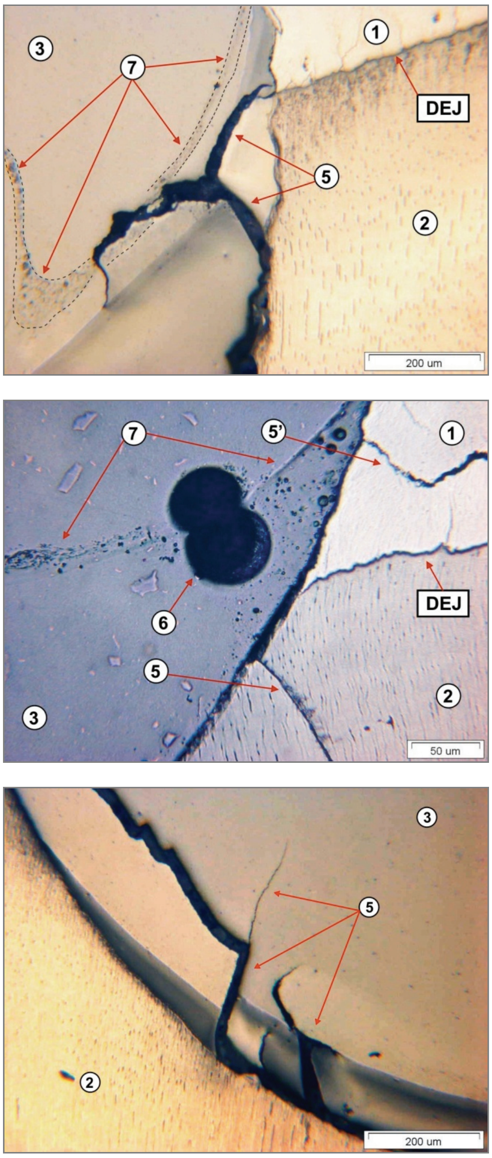

Fig. 8. Microscopic image of tooth section with filling after 100 000 chewing cycles: 1 – enamel, 2 – dentine, 3 – filling, 5 and 5′ – cracks, 6 – gap in the filling structure, 7 – division zone of the consequtive composite layers, DEJ – dentine–enamel junction

Cracks that are present in the dentine structure have a complex and discontinuous nature. Kahler et al. [30] claim that in reality each of the main cracks consists of several microcracks. They also conclude that a cracking process of dentine is strongly dependent on the hydration level of its structure.

4.2. Quantitative analysis of the results

Analyzing the changes in a number of cracks as the function of a number of load cycles, it has been noticed that a number of cracks increases in the consequtive load ranges. The largest increase was found

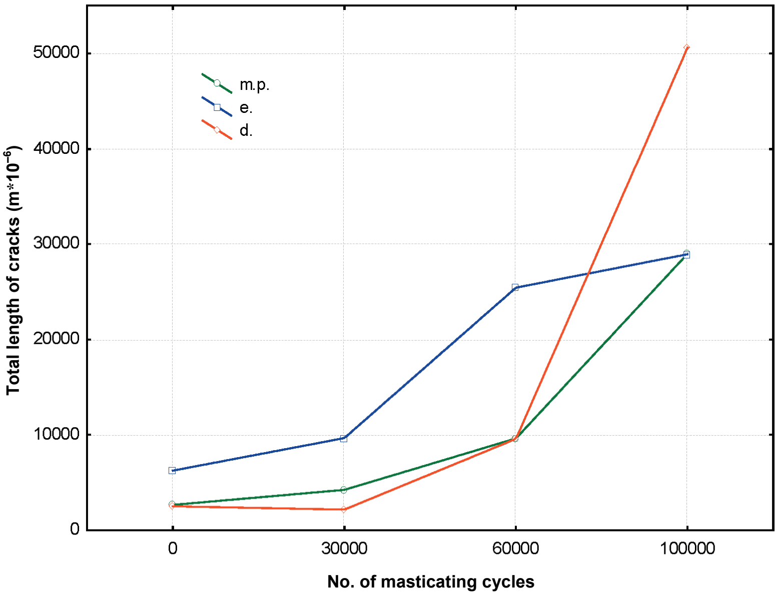

Fig. 9. Total length of cracks versus a number of load cycles:
m.p. – masticating surface area, e. – enamel area, d. – dentine area

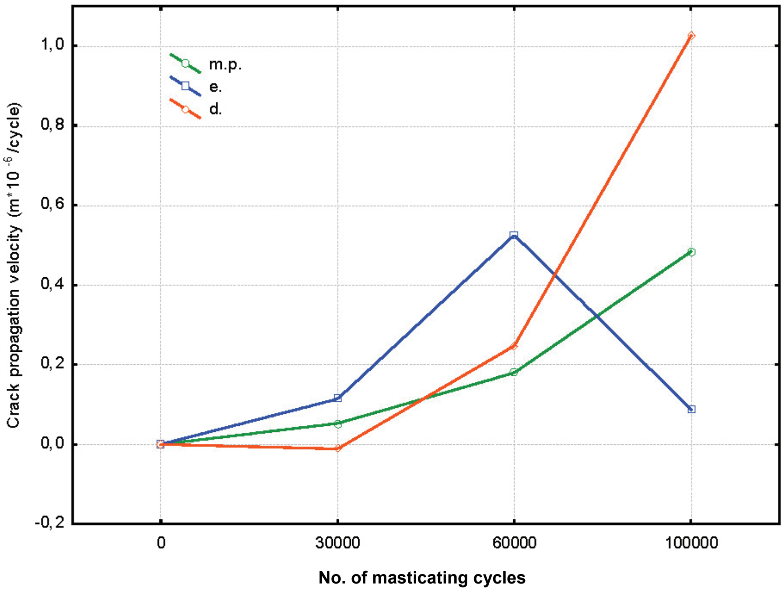

Fig. 10. Propagation velocity of cracks in subsequent load ranges:
m.p. – mastication surface area, e. – enamel area, d. – dentine area

in the dentine area (from 18 to 100), while a maximum average crack length was observed on the chewing surface. These values ranged from 380 µm to 783 µm. In this area, also the longest crack was observed, it reached a length of approx. 3570 µm. Comparing the areas of the tooth examined, it has been stated that the cracks on the masticating surface are most expanded, while the average crack length in the deeper zones was lower. However, in enamel area, especially in the dentine zone, the cracks occurred more often than on the masticating surface.

In figure 9, the curves representing a total length of cracks versus a number of load cycles are shown. On the masticating surface (m.p.) and in enamel area (e.) a moderate increase in a total length of cracks was noticed. It is worth mentioning that in the masticating surface area (m.p.), the growth was higher than that in the enamel area in a range up to 60 000 load cycles. It should be stressed that after 60 000 chewing cycles a total length of cracks in enamel area significantly decreased, while in the dentine area an increase in the length of cracks was the highest.

The analysis of cracking dynamics in relation to a number of load cycles enables degradation process of the tooth–filling system to be predicted.

In the present work, an average propagation velocity of cracks was assumed as a cracking dynamics index, estimated as an average length of crack at a number of load cycles studied, and related to this number of cycles. The curve representing the propagation velocity in the subsequent ranges is presented in figure 10. In the case of dentine area (d.) and masticating surface area (m.p.), a propagation velocity in all subsequent load ranges increased, while in enamel area (e.) this velocity decreased after 60 000 chewing cycles. In the dentine area (d.), a propagation velocity increased after 60 000 chewing cycles. Thus, the most pronounced degradation occurred in the dentine area. The studies conducted indicate that the majority of cracks in the dentine area was formed in the filling material, and not in tooth tissue. Thus, it can be stated that the stress distribution in the dentine area is especially unfavourable because of large differences in mechanical properties of composite and dentine. The values of the modulus of elasticity for these structures are 4.31 GPa and 12–18 GPa, respectively [31]. Crack initiation in the dentine area is favoured by filling geometry. A bottom surface of the filling body is almost perpendicular to the direction of the highest occlusive forces. In a such system, compressive stresses dominate, while in shallower filling zones, stresses are more diverse. Besides the compressive stresses, caused by the vertical occlusal force, there are tensile stresses, resulting from the transfer of the forces caused by the lateral movements of cusps.

5. Summary

1. In the process of chewing, fatigue cracking occurs both in the filling material and in tooth hard tissues adjacent to the filling due to mechanical cyclic loads.

2. Fatigue cracking occurs mainly in the area where the surface of the filling and tooth tissues come into contact, especially in the case of marginal fissure formation.

3. In the composite filling body, structural cracking has also been noticed, such as structural gaps or decohesion of composite layers, which are formed during packing the cavity with a filling material. In special cases, the expansion of the cracks is responsible for fracture of the filling or tooth hard tissue fragments.

4. Comparing the anatomical zones, i.e., masticating surface area, enamel area and dentine area, it can be concluded that the least number of cracks is observed on the masticating surface; however, they are most extensive. The highest number of the cracks of filling occurred in the contact zone with dentine.

5. Analyzing the dynamics of the formation and expansion of cracks with regards to a number of load cycles, it has been founded that on the chewing surface and in the enamel area both an increase in a number and an increase in length have a linear nature. In the contact area with dentine, after a specified long load series a progressive crack development takes place. Under conditions of the studies conducted an accelerated expansion of the cracks occurred after 60 000 cycles.

6. Taking into account mutual interactions of the marginal fissure expansion with fatigue cracking and the fact that there is a critical (in crack dynamics) number of chewing cycles, it can be presumed that the impact of composite filling cracking and adjacent tooth tissues on the durability of the tooth–filling system is crucial.

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