Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

15: 2 (2015) 95-100

COMPOSITES THEORY AND PRACTICE

Niels Modler[1], Werner A. Hufenbach[1], Stephan Gäbler[2]
Robert Gottwald[1], Frank Schubert[1,3], Martin Dannemann[1*]

[1] *Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology (ILK), Holbeinstr. 3, 01307 Dresden, Germany*
[2] *Dental surgery Dr. Gäbler, 01465 Langebrück, Germany*
[3] *Department of Lightweight Structures and Polymer Technology, TU Chemnitz, Germany*
**Corresponding author. E-mail: martin.dannemann@tu-dresden.de*

Received (Otrzymano) 17.10.2014

ENDODONTIC INSTRUMENTS MADE OF FIBRE-REINFORCED POLYMER COMPOSITES - PRELIMINARY FEM AND EXPERIMENTAL INVESTIGATIONS

Conventional needle-shaped instrument tips under ultrasonic excitation for root canal treatment made of nickel titanium (NiTi) alloys achieve a high cleaning performance, especially when inducing the cavitation phenomenon. Nevertheless, their tendency to spontaneous material failure is disadvantageous. Monolithic polymers, e.g. polyamide (PA) significantly reduce this risk, however, instrument tips made of this material are characterised by low cleaning performance. Fibre-reinforced polymers (FRP) exhibit the possibility to bear dynamic loads at higher life cycles than conventional metallic materials. The use of endless fibre-reinforced polymers allows the realisation of instrument tips offering good damage tolerance and cost-efficiency as well as a high cleaning performance. This paper focusses on preliminary numerical and experimental investigations necessary to prove the suitability of fibre-reinforced materials for endodontic instrument tips. The numerical investigations conducted using a standard FE-Method contain simulations of the eigenfrequencies. The accompanying experiments were done for optical detection of the cavitation effects induced by conventional and fibre-reinforced instrument tips. The calculations and tests of the novel instruments made of PA6 reinforced with carbon fibres (CF-PA6) demonstrate a significantly higher cleaning efficiency and a clear failure tolerant structural behaviour compared to conventional polymer and nickel titanium instruments. The investigations show a large number of influencing factors on the operation of fibre-reinforced instruments under ultrasonic excitation. In this context, further tests have to be done to qualify a potential clinical relevance.

Keywords: **endodontic instrument, needle-shaped instrument tip, root canal treatment, cavitation, ultrasonic excitation, fibre-reinforcement, experiment, numerical investigation**

ENDODONTYCZNE NARZĘDZIE WYKONANE Z KOMPOZYTÓW WŁÓKNISTYCH - WSTĘPNE BADANIA FEM I EKSPERYMENTALNE

Konwencjonalne igłowe końcówki do leczenia kanałowego wzbudzane ultradźwiękami wykonane ze stopów niklu i tytanu osiągają wysoką wydajność czyszczenia, szczególnie poprzez wykorzystanie zjawiska kawitacji. Niekorzysta jest ich skłonność do samoistnego uszkadzania materiału. Polimery monolityczne, jak np. poliamid, znacząco zmiejszają to ryzyko, jednak narzędzia wykonane z tego materiału charakteryzują się niską wydajnością samoczyszczenia. Kompozyty włókniste umożliwiają przenoszenie obciążeń dynamicznych i osiąganie wyższej liczby ich cykli niż w przypadku typowych stopów metali. Zastosowanie kompozytów polimerowych wzmacnianych włóknami ciągłymi umożliwia ekonomiczną realizacje końcówek narzędzi o dobrej tolerancji na uszkodzenia oraz dużej skuteczności czyszczenia. Artykuł skupia się na wstępnych badaniach numerycznych i eksperymentalnych koniecznych do ustalenia przydatności komozytów włóknistych do endodontycznych końcówek narzędzi. Badania numeryczne wykonane przy użyciu typowych metod elementów skończonych zawierają symulacje częstotliwości własnych. Towarzyszące badania eksperymentalne zostały wykonane w celu optycznej detekcji zjawiska kawitacji wywołanego zarówno przez konwencjonalne, jak i wzmacniane włóknami końcówki narzędzia. Obliczenia i testy końcówek nowego typu narzędzi wykonanych z poliamidu 6 wzmacnianego włóknami węglowymi (CF-PA6) wykazują wyraźnie wyższą wydajność czyszczenia oraz odporność na uszkodzenia od typowych końcówek z tworzyw sztucznych i stopów niklu i tytanu. Badania wykazały znaczną liczbę czynników wpływających na działanie końcówek wykonanych z kompozytów włóknistych wzbudzanymi ultradźwiękami. W tym kontekście wymagane są dalsze badania w celu potwierdzenia ich przydatności klinicznej.

Słowa kluczowe: **narzędzia stomatologiczne, leczenie kanałowe, kawitacja, ultradźwięki, zbrojenie włókniste, eksperyment, badania numeryczne**

INTRODUCTION

In root canal treatment, cleaning systems with needle-shaped instruments excited in the (ultra-) sonic frequency range are often used when cleaning fluids do not circulate sufficiently in the root canal by simple injection [1, 2]. The particles of the cleaning fluid are excited by means of a vibrating instrument. A high energy application into the fluid (usually more than 10 W/cm²) can induce the phenomenon of cavitation. Thereby small vacuum bubbles (pull phase) are generated in the cleaning fluid, which again implode immediately (push phase). Additionally, dissolved gases are extracted and the cell walls of microorganisms are mechanically broken (plasmolysis) due to the rapid succession of pressure increase and drop. Fast exchange of the fluid in the canal and effective transport of the fluid to the apical region are obtained [3, 4].

Conventional instruments made of stainless steel can be deformed plastically in order to adjust their geometry to the root canal. Their tendency to spontaneous failure due to dynamic loading is disadvantageous, whereby the resulting fractured surface can damage the root canal and removal of the fragment is often complex and expensive. Another typical material for instruments is nickel titanium alloy (NiTi), which exhibits high flexibility due to its pseudo-elastic material behaviour. Thus, good adjustment to the mostly curved root canal is given. However, pre-bending of these NiTi-instruments is not possible and they also tend to spontaneous failure. Nevertheless, instruments made of polymers - usually Polyamide 6 (PA6) - do not have this deficit. However, their much lower stiffness and higher material damping prevent the input of the required amount of energy needed for the cleaning process [5, 6].

The aim of the ongoing research work is to develop a needle-shaped endodontic instrument tip with improved durability and high cleaning efficiency. Fibre-reinforced composites exhibit the possibility to bear dynamic loads at higher life cycles than conventional metallic materials [7]. The use of fibre-reinforced polymers offers the realisation of damage tolerant and cost-effective instruments permitting high cleaning performance. Thus, the first fundamental numerical and experimental investigations on elementary ultrasonically excited cleaning instruments made of endless fibre-reinforced polymers are accomplished. To provide biocompatibility and assure no exposed fibres on the skin of the needle-shaped instrument, the composite material is supposed to be designed as a rod as the core within a polymer outer cone. This can be considered by the application of an additional functional, e.g. protection coating of the rod [8, 9]. The studies presented here were performed on a laboratory scale and examine the influence of the core diameter and material as well as realisation of the cavitation effect for hydrodynamic cleaning by such novel endodontic instrument tips.

The vibration behaviour of needle-shaped instruments and the subsequent cavitation effects within fluid-filled root canals is highly complex; hence stand-alone calculations or measurements are often not meaningful enough to understand all the details. Therefore in terms of preliminary investigations, the first numerical simulations on the vibration behaviour and basic experimental observations on the vibration and cavitation of the needle-shaped instrument tips made of endless fibre-reinforced polymers were carried out in such a way that they complement one another.

ENDODONTIC INSTRUMENTS

Exact calculations of the behaviour of an endodontic instrument causing the cavitation phenomenon is still not a current state of research (see also [10, 11]). This is caused by the complex interaction effected by many parameters and phenomena. The acoustic fields of cavitation bubbles are complex multi-scale and multi-phase systems, which show the phenomena of the space-time dependent generation of structures. Since each bubble already has a highly complex vibration dynamic, interactions of these non-linear oscillators are often described by neglecting specific phenomena [12, 13]. For that reason, orienting numerical and experimental investigations were carried out. The initial numerical simulation is used for a first evaluation of different base designs because precise sample preparations and tests are costly. In accompanying experiments, the functionality of needle-shaped instruments made of fibre-reinforced polymers and excited at ultrasonic frequencies is demonstrated.

The achievable hydrodynamic cleaning performance based on the cavitation effects of an ultrasonically excited endodontic instrument depends on the level of its vibration amplitudes, which are especially influenced by the eigenfrequencies and damping of the instrument as well as the excitation amplitude. The overall vibration system can be discretised into a harmonic excited single-mass oscillator to analyse the relations of these important parameters. Figure 1 shows the endodontic instrument with idealised excitation and vibration (left) as well as the simplified model approach of the vibrational system (right).

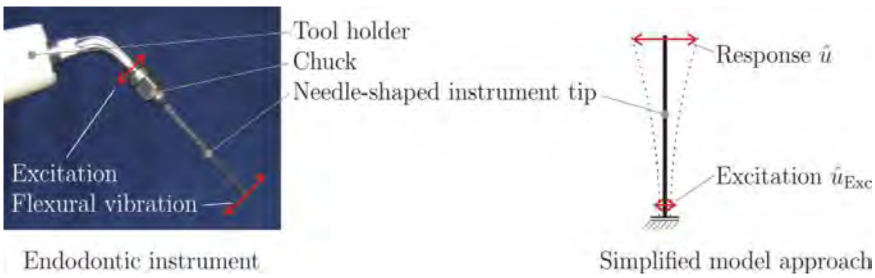

Fig. 1. Endodontic instrument setup (left) and simplified model approach of vibrational system (right)

Rys. 1. Konfiguracja endodontycznego narzędzia (po lewej) i przybliżenie systemu drgającego za pomocą modelu (po prawej)

Assuming that a high cleaning effect is caused by high vibration amplitudes $\hat{u}$, it is advantageous to combine high excitation amplitudes $\hat{u}_{Exc}$ with resonant operating conditions. Furthermore, low damping values lead to additional benefits.

NUMERICAL INVESTIGATIONS

Numerical model and material properties for calculation of eigenfrequencies and vibration amplitudes of needle-shaped composite instruments

The Finite Element Method (FEM) simulation is used for performing preliminary investigations concerning the vibrational behaviour of needle-shaped instrument tips made of a composite material. The FE system ANSYS Classic with its possibility to generate parameterised simulation models permits efficient studies on the relevant parameters (mass, stiffness, damping).

For the novel multi-material instrument, the reinforcing material is built up as a cylindrical core. Especially in the case that fibre-reinforced composites form the core volume, a low-cost manufacturing process such as the pultrusion technique could be used for later production. This core material is surrounded by an outer cone made of PA6 in order to improve the fail-safe properties and to ensure high biocompatibility. The outer geometry of this cone is kept constant within this preliminary FE study and was chosen according to conventional instrument tips (length: L = 22 mm, d_u = = 1.0 mm and d_o = 0.3 mm). The diameter of the core material d_{Core} was varied from 0 to 0.2 mm. Figure 2 shows the used 2D finite element mesh and the resulting 3D finite element axisymmetric model based on PLANE25[1] elements.

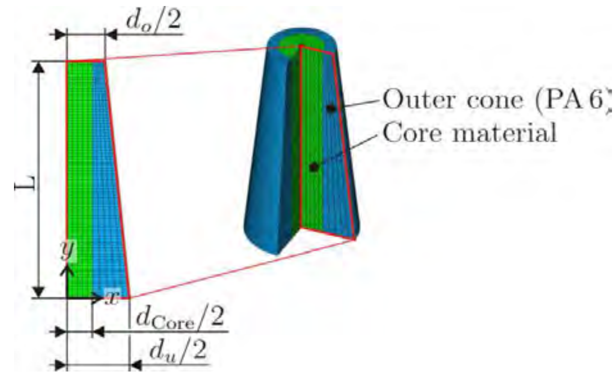

Fig. 2. 2D finite element mesh of axisymmetric volume model of needle-shaped instrument tip

Rys. 2. Dwuwymiarowa siatka elementów skończonych trójwymiarowego osiowego modelu igłowej końcówki narzędzia

Within the modal analysis using the BLOCK LANCZOS method, the nodes at the bottom (y = 0) were fixed. The calculation of the excited steady-state vibration amplitudes includes boundary conditions (harmonic displacement conditions at y = 0) according to the simplified model approach as excitation (see Fig. 1, right).

To gain the first design proposals and evaluate the novel instrument, the metals steel, nickel-titanium alloy (NiTi) and reinforced polymers carbon fibre-reinforced polyamide 6 (CF-PA6) and glass fibre-reinforced PA6 (GF-PA6) as core material at different geometries are investigated. Young's moduli[2] $E_\parallel$ and $E\perp$ as well as the density ρ and damping ratio ξ of the used materials are summarised in Table 1.

TABLE 1. **Material parameters for FE model (known or supposed after [14-16])**

TABELA 1. **Parametry materiałowe użyte w modelu elementów skończonych (znane albo przejęte za [14-16])**

	Material	ρ [g/cm³]	$E_\parallel$ [GPa]	$E_\perp$ [GPa]	ξ [%]
Core	Steel	7.85	210.0	210.0	1.5
	NiTi	6.45	80.0	80.0	2.0
	GF-PA 6	1.98	44.4	3.4	2.0
	CF-PA 6	1.51	144.6	2.9	2.0
Outer cone	PA 6	1.13	1.4	1.4	4.0

In the calculations, the diameter of the core material d_{Core} is varied in steps of 0.01 mm over the given range 0 mm $\leq d_{Core} \leq$ 0.2 mm for the core materials specified in Table 1.

Natural vibrations

High vibration amplitudes are caused by resonant vibration modes with low modal damping. As mentioned, these high amplitudes are important to achieve a high cleaning performance. FE-simulation studies were performed in order to calculate the first eigenfrequency of the needle-shaped multi-material instrument. Assuming a standard instrument tip (polyamide, d_{Core} = 0 mm in Fig. 3) is tuned to the endodontic instrument (see Fig. 1 left), the novel multi-material needle-shaped instrument tip should show similar eigenfrequencies.

Figure 3 shows the change in eigenfrequency due to the core diameter d_{Core} for different reinforcing materials in relation to the mono-material PA6 instrument tip (i.e. d_{Core} = 0 mm).

For all the core materials, a strong dependency of the eigenfrequency on the core diameter was calculated. In the case of fibre-reinforced core materials, higher core diameters lead to a continuous increase in the eigenfrequency. The reason is the high influence on the stiffness, while the instrument mass only slightly increases. In case of the investigated metallic core materials steel and NiTi, an initial decrease at low core diame-

[1] PLANE25 element is an axisymmetric solid element.

[2] The material data are taken from literature or derived using the rule of mixture.

ters can be detected, because the increasing mass dominates over the stiffness increase.

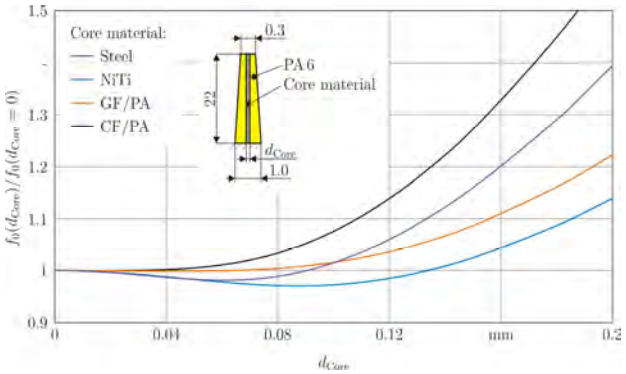

Fig. 3. Influence of core diameter d_{Core} and core material on change in eigenfrequency $f_0(d_{Core})/f_0(d_{Core} = 0)$

Rys. 3. Wpływ średnicy rdzenia d_{Core} i materiału rdzenia na zmianę częstotliwości własnej $f_0(d_{Core})/f_0(d_{Core} = 0)$

From the dynamical point of view, all the investigated material combinations and core diameters should be suitable for use with an endodontic instrument since only minor changes in the eigenfrequencies were calculated ($0.96 < f_0(d_{Core})/f_0(d_{Core} = 0) < 1.60$).

Excited, steady-state vibrations

To analyse the deflection vibration amplitude of the instrument tip and therewith the energy input into the cleaning agent, an analysis of the vibration amplitude spectrum for the identified eigenfrequencies is performed. Figure 4 shows the calculated amplitudes related to the amplitude of the mono-material PA6 instrument tip. To extract the shown values, a harmonic analysis was performed including excitation in the form of a harmonic displacement restriction at the bottom $y = 0$ within the frequency spectrum around the eigenfrequency of interest f_0. Subsequently, the calculated spectrum was analysed and the maximum value $\hat{u}$ was extracted. This calculation was repeated for every core diameter and core material.

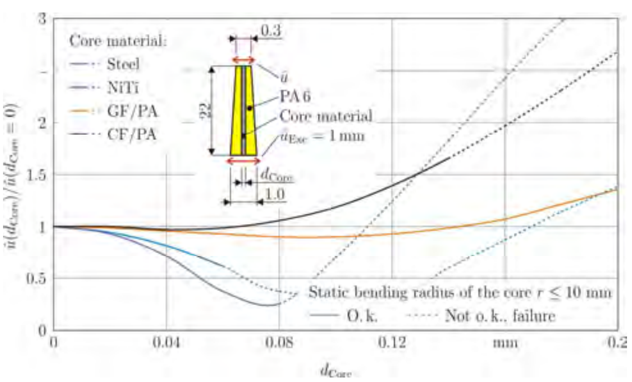

Fig. 4. Comparison of calculated amplitude ratios $\hat{u}(d_{Core})/\hat{u}(d_{Core} = 0)$ in frequency range depending on core diameter d_{Core} at resonance of needle-shaped instrument tip (20 kHz $\leq f_0 \leq$ 36 kHz)

Rys. 4. Porównanie wyliczonych stosunków amplitud $\hat{u}(d_{Core})/\hat{u}(d_{Core} = 0)$ w zakresie częstotliwości zależnym od średnicy rdzenia d_{Core} przy rezonansie igłowej końcówki narzędzia (20 kHz $\leq f_0 \leq$ 36 kHz)

The comparison shows that the used material and diameter of the core influences the height of the resulting maximum amplitude at a defined eigenfrequency. This is caused by stiffness, mass and damping effects. A significant increase in the vibration amplitude by inserting a core material is possible especially using steel or CF/PA. Nevertheless, both the investigated metallic core materials decrease the amplitudes for small diameters, resulting in a lower energy input into the root canal of the tooth. Furthermore, the basic considerations of strength and failure limit the range of usable core diameters. The assumed minimum bending radius of $r = 10$ mm, which should be possible for later applications, limits the usable range to the solid lines in Figure 4. Consequently, only the use of CF/PA or GF/PA as the core material allows one to increase the vibration amplitude of the needle-shaped multi-material instrument.

EXPERIMENTAL PROOF OF CAVITATION EFFECTS

Experimental setup

Systematic preliminary investigations on the cavitation phenomenon caused by specimens made of PA6 and CF-PA6 were performed. Due to the ease of manufacturing, the specimens represent a cylindrical core material without the PA-cone and were manufactured on a laboratory scale for these investigations. The specimens have a diameter of approx. $d = 0.9$ mm and a free length of approx. $L = 15$ mm. The excitation of these specimens was done using the endodontic instrument SATELEC P-MAX (see Fig. 1, excitation frequency approx. $f = 30$ kHz).

Transparent cavities of machinable materials appear to be well suited for the optical detectability of cavitation bubbles. The appearance and quantity of these bubbles influence the cleaning efficiency [17]. Investigations in blind holes of different diameters (1.5 to 3.5 mm) drilled in polymethylmethacrylate (PMMA) were carried out. These cavities represent scaled root canals. Optical acquisition of the results was done using a VISION RESEARCH PHANTOM V7.1 high speed camera.

Results

Although the system is not adjustable concerning its operating frequency and thus does not excite the eigenfrequencies, the results show that high hydro-dynamic activity in the cleaning fluid can be reached by using endless fibre-reinforced instruments. The obtained formation of gas bubbles of both the PA6 specimen and the CF-PA6 specimen is displayed in Figure 5.

It was found that instrument tips made of fibre-reinforced materials lead to visible cavitation effects. Additional findings show that smaller cavities seem to increase the cavitation phenomenon as well as starting the vibration before inserting the instrument tip into the fluid-filled cavity.

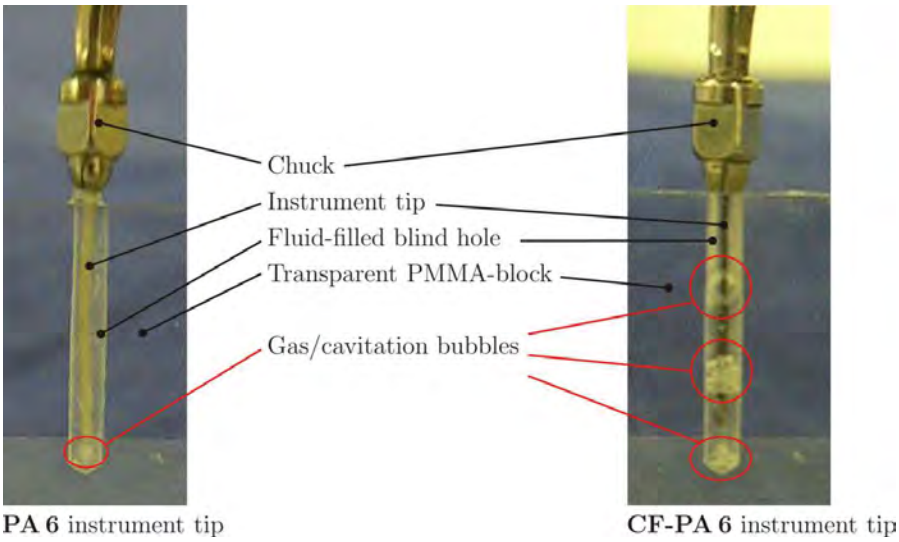

Fig. 5. Cavitation effects at ultrasonic excitation of an endodontic instrument made of PA6 (left) and CF-PA6 (right)

Rys. 5. Zjawiska kawitacyjne przy ultradźwiękowym pobudzeniu endodontycznego narzędzia wykonanego z PA6 (po lewej) i CF-PA6 (po prawej)

Further tests have shown that the performance of instrument tips made of carbon fibre-reinforced thermoplastics is not only significantly increased compared to those of pure polymers but also comparable with those of conventional nickel titanium alloys. Since fibre-reinforced polymers show a damage-tolerant behaviour, which can be adjusted in a wide range, the risk of spontaneous rupture might be reduced.

SUMMARY AND OUTLOOK

The gained results show the complexity of the dimensioning and layout of novel endless fibre-reinforced endodontic instrument tips under ultrasonic excitation. The different influences of geometry, material, excitation and fluid have to be considered within the design process. Within FEM-based parameter studies, it is possible to efficiently investigate the eigenfrequencies of needle-shaped composite structures and to identify the influence of different materials and dimensions as well as the corresponding sensitivity. The goal of these investigations is the design of an instrument tip which exhibits high amplitudes at defined ultrasonic excitation frequencies and thus causes high cavitation effects resulting in an improved cleaning performance.

Using endless fibre-reinforced polymers as material for needle-shaped instrument tips allows one to combine good damage tolerance and low manufacturing costs with high cleaning performance. The calculations and tests of the novel instruments made of CF-PA6 show high cavitation effects and a clear failure-tolerant structural behavior compared to conventional polymer and nickel titanium instruments, respectively.

The research work showed that in practice, the frequency and vibrations vary because of many different non-constant influences on vibration behavior, e.g. insertion rate or contact points on the dentin wall in the root canal. Further investigations, e.g. on the ability of operating at resonant frequency, have to be conducted. A high irrigation effect at a low energy input can be achieved with fibre-reinforced materials, but possible secondary effects especially caused by their temperature dependent stiffness, strength and damping has to be considered. Furthermore, reproducible test methods must be found for the investigation and quantification of failure behavior to qualify a potential clinical relevance.

REFERENCES

[1] Castagna F., Rizzon P., et al., Effect of passive ultrasonic instrumentation as a final irrigation protocol on debris and smear layer removal - a SEM analysis, Microsc. Res. Tech. 2013, 76, 5, 496-502.

[2] v.d. Sluis, L., Ultrasonics in endodontics, Endo 2007, 11, 29-36.

[3] Hülsmann M., Die Anwendung elektro-physikalisch-chemischer Methoden in der En-dodontie, ZWR, 2004, 85-96.

[4] Hülsmann M., Die Aufbereitung des Wurzelkanals, [in:] D. Heidemann (Hrsg), Praxis der Zahnheilkunde, Band: Endodontie. München, Jena: Urban und Fischer, 2001. 80-116.

[5] Macedo R., Verhaagen B., Rivas D.F., Versluis M., Wesselink P., van der Sluis L., Cavitation measurement during sonic and ultrasonic activated irrigation, J. Endod. 2014, 40, 4, 580-583.

[6] Jiang L.M., Verhaagen B., Versluis M., van der Sluis L., Evaluation of a sonic device designed to activate irrigant in the root canal, J. Endod. 2010, 36, 1, 143-146.

[7] Fragoudakis R., Saigal A., Predicting the fatigue life in steel and glass fiber reinforced plastics using damage models, Materials Sciences and Applications, 2011, 2, 596-604.

[8] Wintermantel E., Ha S.W., Biokompatible Werkstoffe und Bauweisen, Springer Verlag, Berlin 1996.

[9] Hufenbach W., Modler N., Gäbler S., Gottwald R., Schubert F., Ultraschallinstrument in Faserverbundbauweise (Ultrasonic instrument for treating teeth of e.g. human, has reinforcing component made of long or continuous fiber composite material, such that long or continuous fibers are extended in parallel along longitudinal axis). Patentanmeldung TU Dresden, DE102010050884A8, November 2010.

[10] Mettin R., Untersuchung und Charakterisierung von Kavitationsblasenfeldern, [in:] D. Bathen, H. Schmidt-Traub (Hrsg.), Innovative Energieträger in der Verfahrenstechnik II, Shaker Verlag, Aachen, 2001. 31-37.

[11] Nowak T., Mettin R., Lauterborn W., Holsteyns F., Frequenzskalierung von Doppelschicht-Kavitationsstrukturen, [in:] U. Jekosch, R. Hoffmann (Hrsg.), Fortschritte der Akustik - DAGA 2008 Dresden, Deutsche Gesellschaft für Akustik e.V. (DEGA), Berlin 2008. 469-470.

[12] Luther S., Mettin R., Lauterborn W., Dynamik akustischer Blasenfelder, [in:] P. Wille (Hrsg.), Fortschritte der Akustik - DAGA 2000 Oldenburg, DEGA, Oldenburg 2000, 686--687.

[13] Mettin R., Ohl CD, Lauterborn W., Modellierung der Strukturbildung bei akustischer Kavitation, [in:] P. Wille (Hrsg.), Fortschritte der Akustik - DAGA 97 Kiel, DEGA, Oldenburg 1997, 192-193.

[14] Flemming M., Roth S., Faserverbundbauweisen: Eigenschaften; Mechanische, konstruktive, thermische, elektrische, ökologische, wirtschaftliche Aspekte, 1. Aufl. Berlin, Springer-Verlag, Heidelberg 1992.

[15] NN. Produktprogramm und Eigenschaften für Tenax® HTA/HTS Filamentgarn, Toho Tenax Europe GmbH, Wuppertal 2008.

[16] NN. Infoblatt No. 4, Ausgewählte Eigenschaften von NiTi-Legierungen, Memory-Metalle GmbH, Weil am Rhein 2009.

[17] Reuver H., von Stetten O., Modelle zur Darstellung und Untersuchung hochdynamischer Effekte bei der Wurzelkanalspülung, Z. Endodontie 2008, 4, 397-409.

