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STATISTICAL AND TRIBOMECHANICAL MODELING OF LOADING AND WEAR OF AUSTENITIC STEEL MEDICAL INSTRUMENTS DURING ROOT CANAL PREPARATION

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СТАТИСТИЧНЕ ТА ТРИБОМЕХАНІЧНЕ МОДЕЛЮВАННЯ НАВАНТАЖЕННЯ І ЗНОШУВАННЯ МЕДИЧНИХ ІНСТРУМЕНТІВ З АУСТЕНІТНИХ СТАЛЕЙ У ПРОЦЕСІ ПРЕПАРУВАННЯ КОРЕНЕВИХ КАНАЛІВ

Purpose. To establish the relationship between insertion-depth kinematic factors, the stress-strain state, tribological wear, and fatigue strength of micro-instruments made of medical austenitic steels 08Kh18N10T and 10Kh17N13M2T during root canal preparation.

The methods. An engineering approach based on contact biomechanics, strength of materials theory, and mathematical and statistical analysis was applied. Axial forces were determined using a linear force-gradient model, while equivalent stresses were calculated according to the Huber–Mises–Hencky criterion in accordance with ISO 3630. Service life was assessed using a high-cycle fatigue criterion, and wear was evaluated using a modified Archard–Kragelsky model. Correlation and regression analyses were performed.

Findings. According to the results of computational modeling, the contact forces increased from 0.60 to 1.80 N for the H-file and from 0.40 to 1.30 N for the Pathfinder CS. The maximum equivalent stresses were 101.7 and 73.4 MPa, respectively, and did not exceed the yield strength limits. Under the specified modeling conditions, the calculated stresses remained below the adopted endurance limits, indicating the potential for high-cycle operation. Strong linear relationships were identified among cyclic workload, insertion depth, and accumulated wear.

The originality. A computational-statistical approach is proposed that combines loading, stress, fatigue, and tribological wear modeling. Relationships among insertion depth, cyclic workload, and wear were quantitatively evaluated for instruments with different geometries.

Practical implementation. The obtained regression relationships can be used to assess trends in the accumulation of wear in endodontic instruments and to substantiate a differentiated approach to instrument design selection under specified operating conditions.

Keywords: *instrument engineering, tribotechnics, biomedical materials science, biomedical data processing, H-file, Pathfinder CS, austenitic steels, stress–strain state, wear, Pearson correlation, regression analysis.*

Introduction. The development, certification, and reliable operation of critical precision instruments for medical device manufacturing and mechanical engineering require

an interdisciplinary approach that combines engineering methods for cutting-tool design, the fundamental principles of medical materials science, and modern technologies for computer-based processing of experimental and biomedical data [1, 2]. Among critical small-sized components, endodontic rod-type instruments occupy a particular position, including H-file reamers and Pathfinder CS micro-instruments, which are structurally designed to operate according to precision micro-planing and cutting mechanisms in complex anatomical dental canals [3, 4].

The specific operating conditions of such instruments are determined by the fact that a miniature cutting shaft with a diameter of 0.15 to 0.45 mm is subjected to combined three-dimensional contact loading in an aggressive biological environment in the presence of significant canal curvature [5, 6]. The simultaneous action of axial compression, alternating bending, the torque required to cut dentin micro-layers, and intensive contact friction results in the development of dislocation fatigue, micro-abrasive wear, and the risk of sudden instrument fracture directly within the tooth root [7, 8]. To prevent such clinical complications, an important engineering task is to perform an in-depth analysis of the physicomechanical properties of the alloys used and to develop validated statistical models linking the technological factors of root canal preparation with the reliable service life of the instruments [9, 10].

Literature analysis. A The reliability of medical micro-instruments has traditionally been investigated along two main directions: assessment of the stress–strain state (SSS) in the contact zone and analysis of the microstructural resistance of alloys to fatigue processes [1, 3]. Shen et al. [1] and Plotino et al. [3] established that up to 80% of instrument fractures are fatigue-related, resulting from repeated cyclic changes between tensile and compressive zones at the outer and inner radii of canal curvature. Using numerical modeling, Zhang et al. [5] demonstrated the critical effect of cross-sectional configuration on mechanical stress concentration: triangular cross-sections, typical of machined H-files, produce high stress concentrations at the peripheral cutting edges, whereas symmetrical quadrilateral profiles, including the Pathfinder CS, exhibit substantially higher torsional stiffness [5, 6].

As indicated by fundamental principles of materials science, high-alloy austenitic steels 08Kh18N10T (AISI 321) and 10Kh17N13M2T (AISI 316Ti) are among the most technologically suitable materials for medical instruments due to their corrosion resistance and ability to retain ductility under moderate cyclic deformation conditions [8, 11]. Zinelis et al. [8] noted that the service life of the instrument shaft is limited not only by its static strength but also by the tribological wear of the working edges [8, 12]. Contact abrasion of the cutting surfaces leads to progressive instrument blunting, an increase in the required axial force applied by the clinician, and secondary overloading of the drive [12, 13].

At the same time, a substantial proportion of published studies has focused on individual aspects, such as material fatigue under cyclic loading, cross-sectional geometry, or torsional stiffness. In the fields of mechanical engineering and medical instrument engineering, comprehensive approaches that integrate cutting kinematics, the strength mechanics of structural alloys, and tribological wear of cutting edges into a unified computational framework remain scarce. Such an integrated approach requires the use of estab-

lished tribological methods [14], design standards [15], and modern mathematical and statistical tools for processing biomedical data, including simple and multiple linear regression modeling, Pearson correlation analysis, and graphical verification of residuals using the StatSoft Statistica environment [16, 17].

Formulation of the unresolved part of the problem and the purpose. To date, the scientific and applied problem of formalizing the relationship between the geometric parameters of conical medical micro-instruments, the level of equivalent elastic stresses in the material, the parameters of linear tribological wear of the working flutes, and their statistical verification using modern mathematical software for biomedical data processing remains unresolved [1, 5, 8, 17].

The objective of this study is to perform analytical modeling and computational-statistical analysis of the loading, stress–strain state, fatigue strength, and tribological wear of endodontic micro-instruments made of medical-grade austenitic steels 08Kh18N10T and 10Kh17N13M2T to quantitatively evaluate their service behavior under specified root canal preparation conditions.

To achieve the stated objective, the following tasks were formulated and addressed:

1. Determine the contact loading forces along the working length of the H-file and Pathfinder CS according to ISO 3630 and evaluate the equivalent stresses in the materials according to the Huber–Mises–Hencky criterion with respect to their yield strengths and fatigue limits.
2. Calculate the parameters of linear tribological wear of the cutting edges as a function of insertion depth and the number of working cycles during root canal preparation.
3. Perform statistical processing of the generated computational datasets using StatSoft Statistica 10.0, determine the Pearson pairwise correlation coefficients, construct scatter plots, and evaluate the parameters of linear regression models describing wear accumulation.

Main part (Results). *Materials Science Analysis and Engineering Modeling of Endodontic Micro-Instrument Loading.* Analytical investigation of the mechanical behavior of rod-type endodontic micro-instruments is based on an assessment of their structural geometry and the physicomechanical properties of the structural materials. The comparative modeling objects are a Hedström file (H-file) and a Pathfinder CS probing instrument, manufactured from high-alloy corrosion-resistant austenitic steels 08Kh18N10T (AISI 321) and 10Kh17N13M2T (AISI 316Ti), respectively.

According to the requirements of ISO 3630, the length of the working conical section of both types of instruments is L = 16 mm, with a nominal taper of k_c = 0.02 mm/mm (2%). The variation in the outer diameter along the working length is described by the following equation:

$$D(x) = D_0 + k_c \cdot x,$$

where D_0=0.15 mm – apical tip diameter; x – insertion-depth coordinate ($0 \le x \le 16$) mm; at the end of the calibrated section, the diameter is D_{16}=0.45 mm. The maximum insertion depth of the instrument into the root canal during clinical passage reaches x = 20 mm.

The geometry of the cross-section has a significant effect on the stress-strain state of the instruments:

– **H-file** – has a triangular cross-section with a radial projection of sharp cutting edges, resulting in high stress concentration along the peripheral cutting lines;

– **Pathfinder CS** – features a rectangular cross-section with a larger metallic cross-sectional area and enhanced torsional stability.

Initial physicomechanical properties of the materials:

– 08Kh18N10T steel (H-file): Young's modulus E = 198 GPa; yield strength $\sigma_{0,2}$ = 205--215 MPa; ultimate tensile strength σ_B = 520--550 MPa; fatigue limit under fully reversed bending $\sigma_{-1} \approx 240$ MPa;

– 10Kh17N13M2T steel (Pathfinder CS): Young's modulus E = 200 GPa; yield strength $\sigma_{0,2}$ = 220--230 MPa; ultimate tensile strength σ_B = 560--590 MPa; fatigue limit $\sigma_{-1} \approx 270$ MPa.

The axial force loading $F(x)$, arising from contact friction and the micro-planing of dentin layers along the root canal walls, is modeled using the following phenomenological function:

$$F(x) = F_0 + \Delta F \cdot x$$

where F_0– initial axial force at the instrument tip upon insertion (N); ΔF – load increase gradient per millimeter of insertion depth (N/mm).

The process constants are as follows:

– H-file: F_0 = 0.60 N; ΔF = 0.060 N/mm;

– Pathfinder CS: F_0 = 0.40 N; ΔF = 0.045 N/mm.

The values of the contact forces as a function of insertion depth are given in Table 1.

Table 1

Calculated loading forces for endodontic micro-instruments

Depth, mm	Force $F_{H\text{-}file}(x)$, N	
	H-file *(08X18H10T)*	Pathfinder CS *(10X17H13M2T)*
0	0.60	0.40
5	0.90	0.625
10	1.20	0.85
15	1.50	1.075
20	1.80	1.30

At the maximum insertion depth ($x = 20$ mm), the contact force reaches 1.80 N for the H-file and 1.30 N for the Pathfinder CS. The stress–strain state is determined by the combined effects of axial compression, elastic bending along the canal axis, and the contact torque associated with dentin cutting. The equivalent mechanical stresses according to the Huber–Mises–Hencky criterion are:

– H-file: σ = 101.7 MPa;

– Pathfinder CS: σ = 73.4 MPa.

The obtained stress values do not exceed the yield strengths of the materials ($\sigma_{0,2}$ = 205--215 MPa and 220--230 MPa, respectively), indicating that the instruments

remain within the purely elastic deformation regime under the specified loading conditions. The corresponding static safety factors are $n = 2.02$ and $n = 3.00$, respectively.

The calculated working stresses amount to 42.4% and 27.2% of the adopted fatigue limits of the investigated steels, respectively. This ratio indicates that, under the adopted loading conditions, the maximum calculated stresses remain below the stress levels used to assess high-cycle fatigue. Therefore, for the applied loading model and the adopted reference life of 10^5 cycles, no indication of reaching the adopted fatigue-strength limit was identified.

The kinetics of linear tribological wear of the working flutes of the micro-instrument is calculated using a modified Archard–Kragelsky wear model equation:

$$W = k \cdot F \cdot x \cdot N,$$

where k – tribological degradation coefficient of the steel–dentin pair; F – contact force (N); x – insertion-depth coordinate (mm); N – number of working cycles. For the adopted computational parameters, the coefficient k is 10^{-8}.

To construct Table 2, the calculations were performed at a fixed maximum insertion depth of $x = 20$ mm and the corresponding contact forces of $F = 1.80$ N for the H-file and $F = 1.30$ N for the Pathfinder CS. Thus, the reported values characterize wear accumulation with an increasing number of working cycles at a specified maximum loading level.

The summarized dynamics of wear accumulation are presented in Table 2.

Table 2

Kinetics of linear wear of endodontic micro-instruments as a function of operating cycles

Number of working cycles N	H-file wear, WH−file	Pathfinder CS wear, WPathfinder
0	0	0
10	0.0000036	0.0000026
20	0.0000072	0.0000052
30	0.0000108	0.0000078
40	0.0000144	0.0000104
50	0.000018	0.000013
60	0.0000216	0.0000156
70	0.0000252	0.0000182
80	0.0000288	0.0000208
90	0.0000324	0.0000234
100	0.000036	0.000026
110	0.0000396	0.0000286
120	0.0000432	0.0000312
130	0.0000468	0.0000338
140	0.0000504	0.0000364
150	0.000054	0.000039

After 100 operating cycles, the wear value for the H-file is 0.000036, compared with 0.000026 for the Pathfinder CS. This corresponds to a 38.5% higher blunting rate of the cutting edges for the H-file. Within the adopted model, this difference is attributed to the higher calculated contact loading of the H-file compared with the Pathfinder CS. At the same number of cycles, this results in a greater accumulated wear value for the H-file.

According to the data presented in Table 3, the **CYCLES** variable has a mean value of $\overline{N} = 75.00$, with a minimum of 0.00 and a maximum of 150.00 cycles, while the standard deviation is дорівнює $S = 47.61$. The **DEPTH** variable is characterized by a mean value of 10.00 mm (minimum 0.00 mm, maximum 20.00 mm), with a standard deviation of $S = 6.35$ mm.

Table 3

Descriptive statistics of the investigated parameters using StatSoft Statistica 10.0

Variable	Number of observations (Valid N)	Mean	Minimum	Maximum	Standard Deviation
CYCLES	16	75	0	150	47.6095
DEPTH	16	10	0	20	6.3503
W_HFILE	16	0.000028	0	0.000054	0.000017
W_PATH	16	0.00002	0	0.000039	0.000012

The analysis of the tribological characteristics shows that the mean level of linear wear for the triangular H-file (W_HFILE) is 0.000028, ranging from 0.00000 to 0.000054, with a standard deviation of 0.000017. For the rectangular Pathfinder CS instrument (W_PATH), the mean wear value is 0.000020 (minimum 0.00000, maximum 0.000039), with a standard deviation of 0.000012. The lower measures of dispersion observed for the Pathfinder CS indicate greater stability and lower variability of its tribological state under intensive cyclic loading.

Correlation analysis of the interaction between kinematic and tribological parameters. To assess the strength and direction of the relationship between the kinematic factors governing the movement of endodontic micro-instruments and the intensity of their surface degradation, a correlation analysis was performed. The strength of the linear deterministic relationship was evaluated using the Pearson linear correlation coefficient (r) at a statistical significance level of $p < 0.05$. The results of the correlation analysis obtained using the StatSoft Statistica 10.0 environment for a sample of $N = 16$ observations are presented in Table 4.

Table 4

Pearson pairwise correlation matrix for kinematic and tribological parameters using StatSoft Statistica 10.0

Variable	CYCLES	DEPTH	W_HFILE	W_PATH
CYCLES	1	0.9912	0.9985	0.9978
DEPTH	0.9912	1	0.9924	0.9919
W_HFILE	0.9985	0.9924	1	0.9991
W_PATH	0.9978	0.9919	0.9991	1

Analysis of the Pearson pairwise correlation matrix revealed very strong positive linear relationships between the variables under study, with correlation coefficients ranging from 0.9912 to 0.9991. In particular, the correlation coefficient between the number of operating cycles and accumulated wear was (r = 0.9985) for the H-file and (r = 0.9978) for the Pathfinder CS. The correlation coefficients between insertion depth and accumulated wear were (r = 0.9924) and (r = 0.9919), respectively.

The high correlation coefficients should be interpreted taking into account that the analyzed data were generated from specified deterministic computational relationships. Therefore, the obtained coefficients primarily characterize the consistency of the model parameters with one another and confirm that their relationships are close to linear. They should not be interpreted as independent evidence of clinical causality or of an experimentally established relationship.

Regression modeling of the dynamics of tribological wear of instrument cutting edges. Quantitative assessment of the kinetics of surface degradation and the development of predictive models were performed using the multiple and simple linear regression module (*Multiple Regression*) in the StatSoft Statistica 10.0 environment. The accumulated linear wear (W) was taken as the dependent response variable (Y), while the cyclic operating history of the instrument during root canal preparation (N) was used as the independent predictor (X).

For visual representation of the identified relationships, regression models with linear approximation were constructed using the two-dimensional *Scatterplots* module separately for the H-file and the Pathfinder CS probing instrument (Figs. 1 and 2).

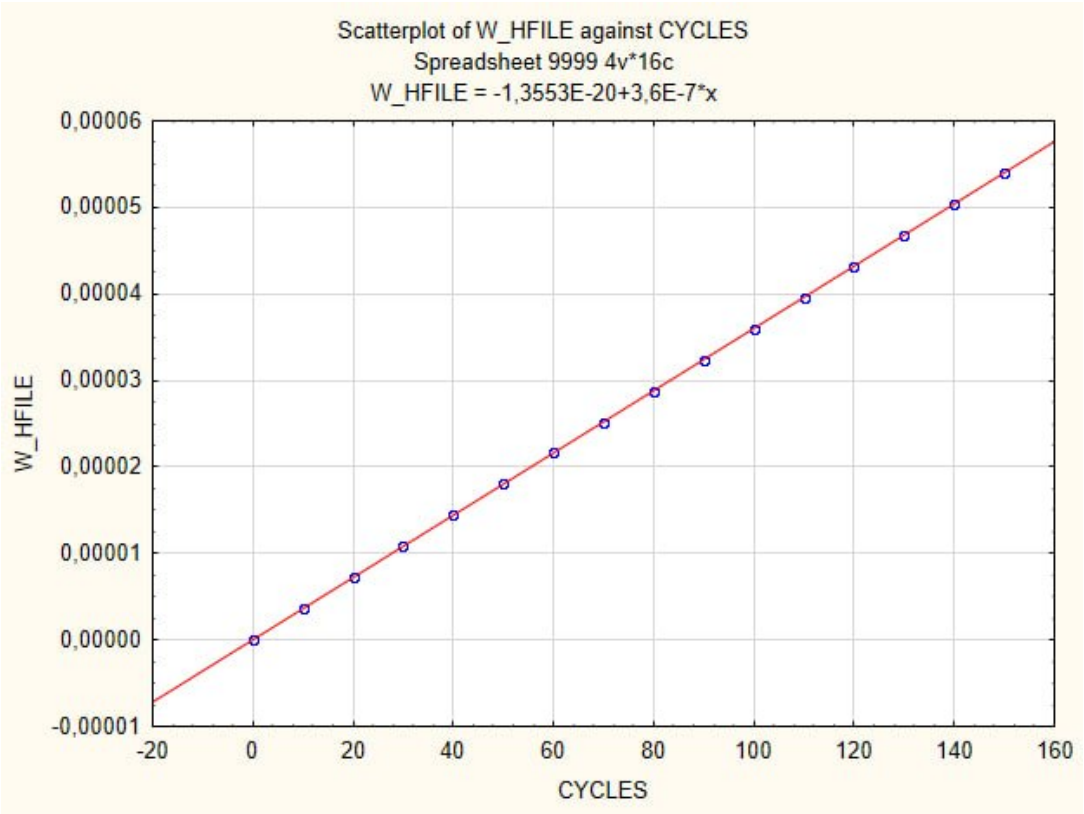


Fig. 1. Two-dimensional Scatterplot and linear regression model of accumulated wear $W_{H\text{-файл}}$ as a function of operating cycles

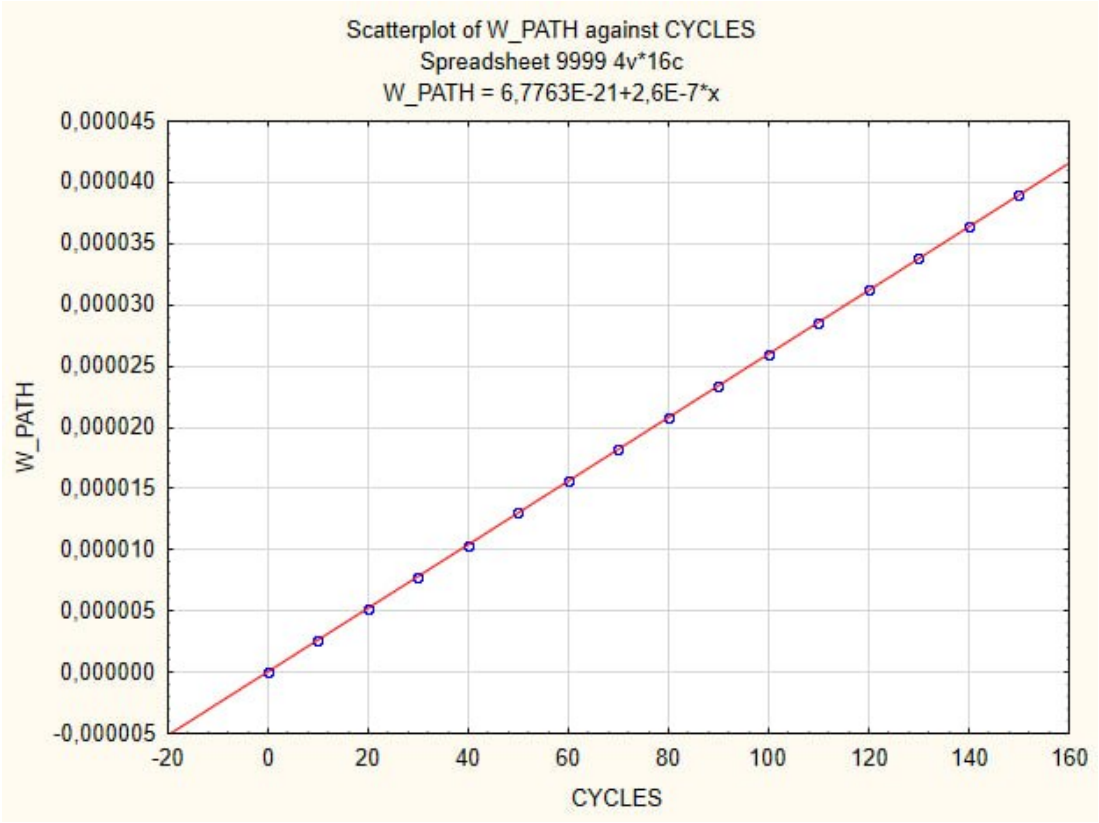


Fig. 2. Two-dimensional Scatterplot and linear regression model of accumulated wear $W_{Pathfinder}$ as a function of operating cycles

Visual analysis of the presented scatter plots (see. Figs. 1 and 2) shows an almost complete agreement between the calculated values and the linear regression relationship, which is consistent with the high values of the correlation and coefficient of determination. The approximation equations automatically generated by the Statistica software and displayed directly on the graphs are as follows:

– for the H-file: $W_{H\text{-}file} = -1{,}3553 \cdot 10^{-20} + 3{,}6 \cdot 10^{-7} \cdot x$ (see Fig. 1);
– for the Pathfinder CS: $W_{Path} = 6{,}7763 \cdot 10^{-21} + 2{,}6 \cdot 10^{-7} \cdot x$ (see Fig. 2).

The intercepts of the equations are practically equal to zero (10^{-20}, and 10^{-21}), which mathematically confirms the absence of wear at the initial point ($N = 0$). Comparison of the slope coefficients shows that the tribological wear rate of the triangular-profile H-file ($3{,}6 \cdot 10^{-7}$) is 38.5% higher than that of the Pathfinder CS with a rectangular cross-section ($2{,}6 \cdot 10^{-7}$), which is in full agreement with the analytical calculations based on the Archard–Kragelsky wear model.

Conclusions. A comprehensive engineering, materials-science, and statistical analysis of the stress–strain state, fatigue strength, and tribological wear of endodontic micro-instruments made of austenitic steels 08Kh18N10T and 10Kh17N13M2T during root canal preparation in accordance with ISO 3630 was performed. According to the results of computational modeling, increasing the insertion depth from 0 to 20 mm results in a linear increase in the axial force, reaching 1.80 N for the H-file and 1.30 N for the Pathfinder CS. The maximum equivalent stresses according to the Huber–Mises–Hencky criterion are 101.7 and 73.4 MPa, respectively, and, based on the adopted mechanical properties of the materials, do not exceed the corresponding yield

strengths. The maximum calculated stresses amount to 42.4% and 27.2%, respectively, of the adopted fatigue limits of the investigated steels. Under the specified modeling conditions, this corresponds to operation in the high-cycle fatigue regime for the adopted reference life of 10^5 cycles. This result characterizes the calculated safety margin with respect to the adopted fatigue-strength criterion and does not replace experimental assessment of the actual service life of the instrument.

Statistical analysis of the computational dataset using StatSoft Statistica 10.0 revealed very strong positive correlations between the number of cycles, insertion depth, and accumulated wear ($r = 0.9912–0.9991$; $p < 0.0001$ for the presented calculations). Given the deterministic nature of the input data, these coefficients characterize the consistency of the adopted model relationships. For the H-file, the calculated wear accumulation rate is 38.5% higher than that for the Pathfinder CS, indicating a significant effect of the instrument geometry and contact loading level on its tribological behavior.

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АНОТАЦІЯ

Мета. Встановлення взаємозв'язку між кінематичними факторами заглиблення, напружено-деформованим станом, трибологічним зношуванням та втомною витривалістю мікроінструментів із медичних аустенітних сталей 08Х18Н10Т та 10Х17Н13М2Т при формуванні кореневих каналів зуба.

Методика. Застосовано інженерний підхід на основі контактної біомеханіки, теорії опору матеріалів та математико-статистичного аналізу. Осьові зусилля визначено за моделлю лінійного силового градієнта, еквівалентні напруження - за критерієм Губера–Мізеса–Генкі за ISO 3630. Довговічність оцінено за критерієм багатоциклової втоми, зношування - за модифікованою моделлю Архарда–Крагельського. Проведено кореляційно-регресійний аналіз.

Результати. За результатами розрахункового моделювання встановлено зростання контактних сил від 0.60 до 1.80 Н для Н-файлу та від 0.40 до 1.30 Н для Pathfinder CS. Максимальні еквівалентні напруження становили 101.7 та 73.4 МПа і не перевищували границь плинності. За заданих умов моделювання розрахункові напруження залишалися нижчими за прийняті межі витривалості, що свідчить про можливість багатоциклової роботи. Виявлено тісні лінійні зв'язки між циклічним напрацюванням, глибиною заглиблення та накопиченим зносом.

Наукова новизна. Запропоновано комплексний розрахунково-статистичний підхід до оцінювання експлуатаційної поведінки ендодонтичних мікроінструментів, що поєднує моделювання навантаження, напружень і втоми з аналізом трибологічного зношування. Кількісно оцінено взаємозв'язок глибини заглиблення, циклічного напрацювання та зносом для інструментів різної геометрії.

Практична значимість. Отримані регресійні залежності можуть бути використані для оцінювання тенденцій накопичення зносу ендодонтичного інструментарію та обґрунтування диференційованого підходу до вибору конструкції інструмента за заданих умов експлуатації.

Ключові слова: *інструментальне машинобудування, триботехніка, медичне матеріалознавство, обробка біомедичних даних, Н-файл, Pathfinder CS, аустенітні сталі, напружено-деформований стан, знос, кореляція Пірсона, регресійний аналіз.*

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