UDC 621.833.15 DOI: 10.18372/0370-2197.1(106).19820

O. O. MIKOSYANCHYK[1]*, O. A. ILINA*[1]*, R. G. MNATSAKANOV*[1]*, S. A. BESPALOV*[2]*,*
O. P. YASHCHUK[1]*, O. I. KUSHCH*[3]

[1]***State University "Kyiv Aviation Institute", Ukraine***

[2]***National Academy of Sciences of Ukraine***

[3]***National Transport University, Ukraine***

ANALYSIS OF THE STRESS-STRAIN STATE OF THE GEARING OF A GEAR PUMP IN THE ANSYS SOFTWARE PACKAGE

The aim of the work was to evaluate the stress-strain state in the zone of tooth engagement under friction when modeling the gear engagement of a gear pump in ANSYS Workbench. It was found that with an increase in the contact Hertzian stress from 180 to 555 MPa, the depth of the zone of distribution of equivalent Mises stresses and the depth of localization of the maximum equivalent Mises stresses increased by 20% and 23%, respectively. The analysis of the tangential stress diagrams (τ_{xy}) in the cross-section of the teeth shows that in the contact zone, the tangential stresses vary in magnitude and sign. The diagrams have two extremes, and the value of the maximum stresses on the leading surface (the initial gear tooth head) is approximately 10-15% lower than the stresses on the trailing surface (the initial wheel tooth leg). High discrepancies in determining the maximum tangential stresses in the simulation model of gearing under rolling conditions with slippage according to the Belyaev formula and in modeling have been established. The calculation formulas for determining the magnitude and sign of the maximum tangential stresses in the zone of engagement of teeth with the greatest slippage are proposed, which are consistent with the results of finite element modeling.

Keywords: *modeling, gearing, stress-strain state, gear pump.*

Introduction. Among the factors affecting the reliability of friction pairs, friction and wear processes occupy a special place. Evaluation of these processes is difficult, since their kinetics depends on the specific pressure between the interacting surface layers, microstructural changes in the surface layer, and chemical reactions at the lubricant-metal interface. The service life, operational reliability, structural strength, technical and economic performance of machine and mechanism parts are largely determined by the mechanical properties of the steels and alloys from which they are made. Gears are the most heavily loaded parts in the running gear of vehicles. They operate under conditions of shock-cyclic contact load with rolling and slipping. The bearing capacity of a gear is determined by such tooth characteristics as contact strength, fatigue bending strength, and wear resistance (more often fatigue or abrasive wear resistance). Therefore, the most common causes of failure are a decrease in tooth strength at their base, fatigue crumbling of the contact surface, and tooth profile wear [1].

In addition to the complexity of the wear and seizure processes, the insufficient reliability of calculated estimates of wear resistance and, consequently, the durability of gear teeth may be due to additional reasons - changes in the geometric, kinematic, and load parameters of the contact during wear, as well as the mutual influence of various tooth damages [2].

For gears, changes in the shape of friction surfaces lead to significant changes in friction modes - as a result of wear, the radii of curvature of the contact surfaces change, and, consequently, the normal contact stresses and friction coefficient [3]. The kinematic parameters of the contact, such as rolling and sliding speeds, change accordingly.

In modern conditions, the finite element method is increasingly used to analyze the contact interaction of gearing, which allows to obtain a reliable picture of the distribution of deformations and stresses on the contact surface and in the depth of the tooth. There is an urgent task of choosing software for constructing the geometry of the gearing and comparing the results of geometric and finite element modeling with classical methods for assessing stresses in local contact.

Review of publications and analysis of unsolved problems. The dominant types of gear failure are fatigue failure, abrasive wear, and overload tooth failure, which account for 77% of all failures. Research results show that dynamic loads have a significant impact on these types of gear failure during operation. They occur during gear operation and are divided into internal and external. The source of internal dynamic loads is the gear wheels of the transmission, which operate under load conditions when performing useful work [4].

Residual stresses have a significant impact on the endurance limit of the wheel tooth material. For high-hardness steels, the presence of compressive stresses leads to a significant increase in the endurance limit, and tensile stresses to a decrease. In turn, the nature (sign) of the residual stresses depends not only on the processing methods but also on the modes of their implementation. Wear of teeth made of hardened and low-plastic materials is primarily caused by the roughness of the machined surfaces, decreasing with decreasing roughness. This is confirmed by studies on samples made of hardened U8 steel, which showed that reducing the roughness from 4.7 to 2.9 microns reduced wear by 30%. The strengthening (riveting) of the surface layers of the teeth with shot after heat treatment significantly increases the fatigue strength, depending on the initial (before heat treatment) surface roughness. The endurance limit increases with decreasing roughness [5].

The same amount of deformation in the surface layers of the contact surfaces of gears, depending on the gear material, can lead to their brittle/viscous fracture or fatigue failure [6]. It is effective to use physical and mathematical models [7] and to assess the stress-strain state by the load distribution in the contact zone, for example, by polarization-optical and other methods [8].

According to the theory of N.P. Suh [9], the initiation of destructive processes in the materials of parts is often initiated by the presence of stress zones at a certain depth of the surface layer. The results of computer modeling in [10] confirm the validity of this theory and make it possible to construct a generalized scheme of the location of the identified characteristic areas with stresses at the depth of the surface layer of a polymeric homogeneous material of samples in relative moving and stationary states. The studies show that in the process of moving the contacting areas from the base of the protrusions to the top, in the surface layer of the polymeric material of the tribo-constriction samples, the depth of the considered local regions does not change significantly.

An analysis of the results of studies [10] conducted by computer modeling shows that knowing the parameters of sample contact, the relative location of local regions, and the thickness of the active surface layer, it is possible to purposefully change the conditions, providing the most favorable friction modes in tribo-conjugation.

The general regularities and features of the stress-strain state of surface layers in the areas of protrusions were revealed depending on the thickness of the deformed layer, its stress state, the shape of the protrusions, their height and pitch, and the level of load on the mating parts [11].

Work [12] analyzed the relationship between the relative speed of movement of friction surfaces and elastic deformation in the lubricating layer, taking into account the basic provisions of the thermodynamic theory of structural states of the boundary lubrication regime [13].

Thus, to model the gearing and analyze the distribution of contact stresses in the meshing zone, it is necessary to take into account the actual operating conditions of the unit, which will make it possible to determine the zones of distribution of equivalent stresses and assess the depth of their localization.

The aim of the study was to evaluate the stress-strain state in the zone of tooth engagement during friction in the modeling of gear engagement of a gear pump.

The gearing model. The gear model was built in Dassault Systems Catia V5 R30 and exported to ANSYS Workbench 2019 R3.

The parameters of the gear when building the model: gear module: m = 3.175; number of teeth: n = 12; gear width: b = 20 mm; wheel material: 30KhGSA; Young's modulus: 215 GPa; Poisson's ratio: 0,3.

In the contact zones of the teeth, the most detailed mesh was created to obtain accurate results: the size of the mesh edge is 150 microns (Fig. 1).

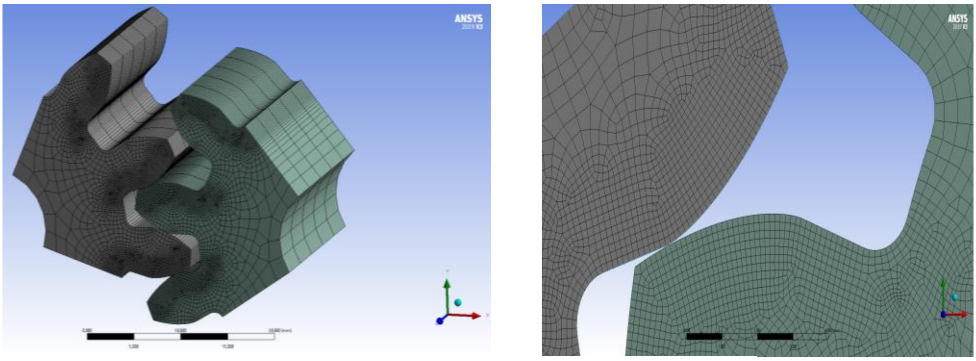

Fig. 1. Gearing model in ANSYS Workbench.

Given that the surface layers of the contact surfaces harden during friction, the use of the ANSYS software package allows us to take this factor into account and perform a calculation that corresponds to the strength characteristics of the material. The problem was solved in a three-dimensional formulation using tetrahedral finite elements with quadratic interpolation of the displacement field and the corresponding finite elements for the surface-to-surface contact.

In order to analyze the distribution of contact stresses in the tooth meshing zone, the rotation of the drive gear with a rotation range of 60 degrees clockwise was set. During the modeling, the minimum friction coefficient in ANSYS software was chosen to be 0.1. The assessment of the stress-strain state of the gearing was carried out at different stages of engagement, with special attention paid to the zone of tooth slippage where stresses can reach the maximum permissible values (Fig. 2).

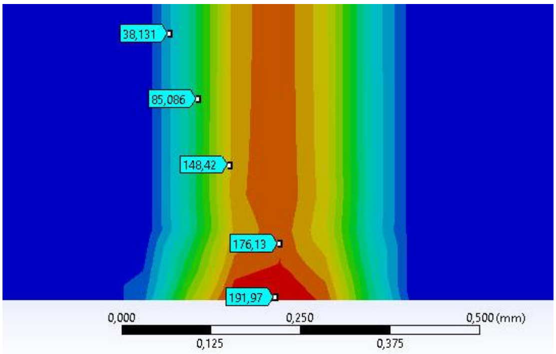

Fig. 2. Evaluation of the stress-strain state of a gear pair in the slip zone at the contact pad.

Evaluation of the stress-strain state of the gearing during modeling. The stress-strain state of the contact surfaces was evaluated at the maximum Hertzian contact stresses in the meshing zone of 180, 380, and 555 MPa (Fig. 3, Table 1).

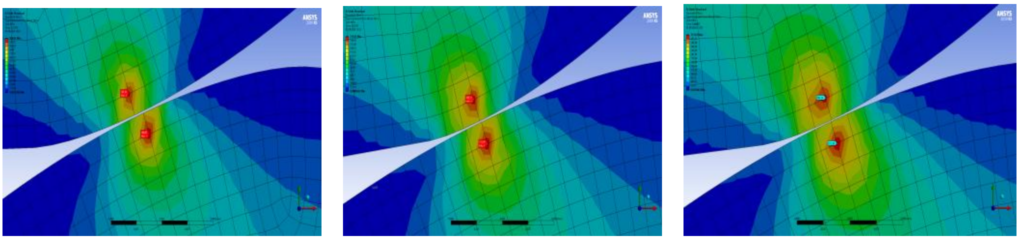
a b c

Fig. 3. Zone of distribution of equivalent Mises stresses in the gearing at contact Hertzian stresses of 180 MPa (a), 380 MPa (b), and 555 MPa (c).

Table 1

Components of the stress-strain state of the gearing

Calculated contact stress by Hertz, MPa	Maximum equivalent stresses according to Mises stresses, MPa	The depth of the distribution zone of equivalent stresses by Mises, µm	Depth of the largest equivalent stresses according to Mises, µm
180	100	160	100
380	212	180	110
555	312	200	130

The analysis of the simulation results showed that with an increase in the Hertzian contact stress from 180 to 555 MPa, the depth of the zone of distribution of equivalent Mises stresses increases by 20%, while the depth of localization of the largest equivalent Mises stresses also increases by 23%. Comparison of the calculated values of contact stresses in the gearing according to the Hertz formula ($\sigma_{\max}$) and the maximum depth equivalent Mises stresses (σ_{depth}^{eq}) by the finite element method corresponds to the ratio specified in [14]:

$$\sigma_{depth}^{eq} = 0{,}5\sigma_{\max} \tag{1}$$

Non-stationary operating conditions of gears, start-stop modes lead to cyclic changes in contact loads, which cause such surface destruction as chipping, wear, deformation, etc.

Experimentally and theoretically, it has been established that tooth fracture occurs under the influence of shear stress [15-17], the maximum of which is achieved at a depth of 1...2 % of the rolling body diameter. For gearing, the radius of curvature is determined by the formula $\rho = 0.5d_w\sin20°$. In the selected NSH-39M gear pump with d_w = 44.5 mm and radius of curvature ρ = 7.61 mm, the calculated depth of localization of the maximum tangential stresses is ≈ 76....152 µm, which corresponds to the depth determined using ANSYS software only at a contact Hertzian stress of 180 MPa (Table 2). With an increase in the Hertzian contact stress to 555 MPa, the depth of localization of the maximum tangential stresses is 210 µm.

Table 2

Magnitude of tangential stresses and their localization in the gearing

Calculated contact stress by Hertz, MPa	Tangential stresses in modeling (Shear Stress), MPa	Calculated maximum tangential stress according to Belyaev, MPa	Depth of localization of maximum tangential stresses in modeling, µm
180	-38.85...+69.017	54.72	125
380	-69.01…+110.49	115.52	187
555	-89.02 …+167.84	168.72	210

Tensile stresses lead to the initiation and development of a crack, which causes tooth fracture. The modeling showed that the tensile stresses in the tooth pedicle reach a maximum at single-pair engagement (Fig. 4).

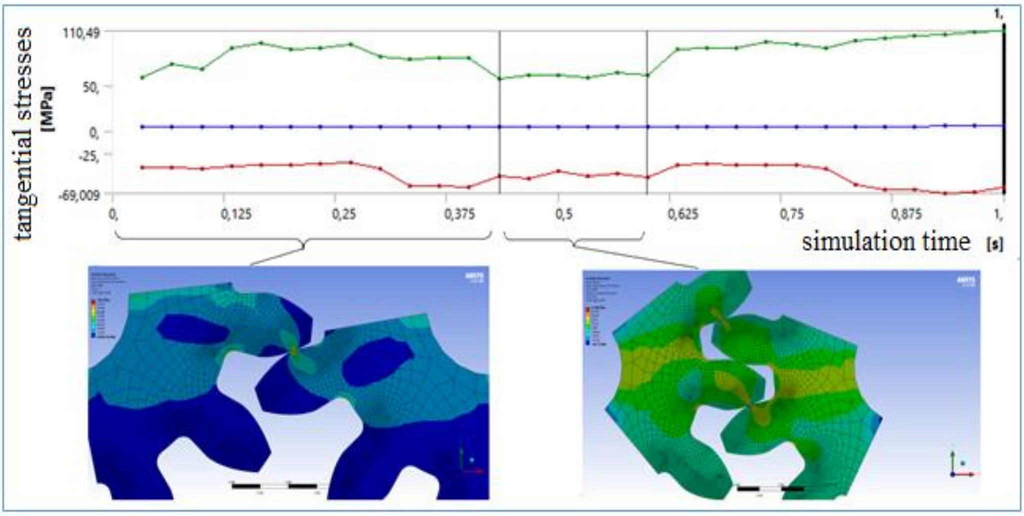

Fig. 4. Stress-strain state and distribution of tangential stresses at a maximum contact stress of 380 MPa.

The analysis of the tangential stress diagrams (τ_{xy}) in the cross-section of the teeth shows that in the contact zone, the tangential stresses vary in magnitude and sign. The diagrams have two extremes, and the value of the maximum stresses on the leading surface (the initial gear tooth head) is approximately 10-15% lower than the stresses on the trailing surface (the initial wheel tooth leg) (Fig. 5).

Under rolling conditions with slipping, the value of the maximum Belyaev tangential stresses is calculated by the formula:

$$\tau_{\max} = 0{,}304\sigma_{\max} \tag{2}$$

Comparison of the results of the maximum tangential stresses in the gearing obtained by modeling and using formula (2) (Table 2) revealed high discrepancies of up to 20 % at the lowest selected Hertzian contact stress, which was 180 MPa.

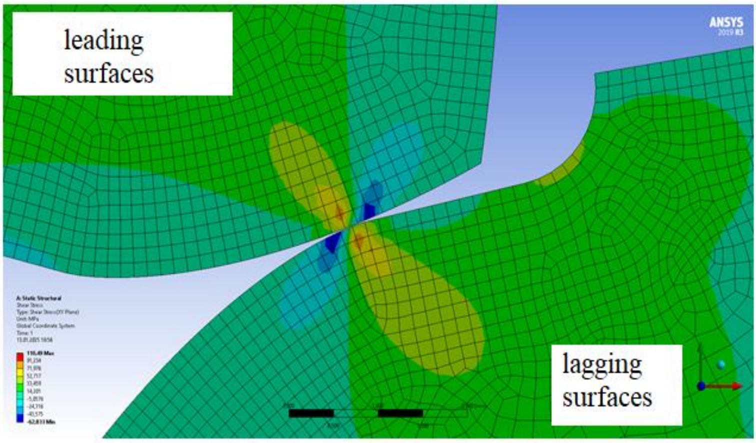

Fig. 5. Diagrams of tangential stresses in the gearing in the XY plane at the maximum contact stress according to Hertz of 380 MPa.

With an increase in the Hertzian contact stress to 380 and 555 MPa, the discrepancy in determining the maximum tangential stresses decreases to 4.5 and 0.5 %, respectively. We assume that the finite element method used in modeling the gearing in ANSYS Workbench is a more accurate and versatile method, since it is based on the fundamental equations of elasticity. ANSYS technologies allow modeling phenomena at the level of solving linear and nonlinear, stationary and nonstationary spatial problems of deformable solid mechanics and structural mechanics (including nonstationary geometrically and physically nonlinear problems of contact interaction of structural elements) [18].

The modeling results confirm that during the operation of a gear transmission, the contact point of the teeth is moved by their working surfaces, which leads to the appearance of tangential stresses in them that vary in magnitude and sign. This nature of the load can explain the process of fatigue microcracks and fatigue chipping of the tooth material. Table 3 shows the calculated values of tangential stresses (Shear Stress) for one of the phases of engagement with the greatest slippage, determined according to the proposed dependencies based on the simulation of the gearing operation of the NSH-39M gear pump when assessing the stress-strain state in the zone of tooth engagement during friction:

$$\tau_{\min} = -(\sigma_{\max})^{0{,}71} \tag{3}$$

$$\tau_{\max} = +(\sigma_{\max})^{0{,}81} \tag{4}$$

Table 3

Comparison of tangential stresses in modeling and calculations

Calculated contact stress by Hertz, MPa	**Tangential stresses in modeling (Shear Stress), MPa**	**Calculated tangential stresses (Shear Stress, MPa) according to formulas (3) and (4)**
180	-38.85...+69.017	-39.9…+67.1
380	-69.01…+110.49	-67.9…+123
555	-89.02 …+167.84	-88.8…+167

The presented calculated results of the magnitude and sign of tangential stresses in the tooth, obtained by formulas (3) and (4), are in good agreement with the results of the finite element method for modeling the gearing in ANSYS Workbench in the range of maximum contact stresses in the gearing, 180-555 MPa.

Thus, the use of automated calculation systems greatly facilitates the process of obtaining functional dependencies for assessing the stress-strain state with subsequent analysis and visualization of the results.

Conclusions

1. When modeling the gear meshing of a gear pump, it was found that with an increase in the Hertzian contact stress from 180 to 555 MPa, the depth of the zone of distribution of equivalent Mises stresses and the depth of localization of the maximum equivalent Mises stresses increased by 20% and 23%, respectively.

2. The change in tangential stresses when modeling the gearing in ANSYS Workbench in the cross-section of the teeth in terms of magnitude and sign was determined; the value of the maximum stresses on the leading surface is 10-15% lower than the stresses on the trailing surface.

3. The calculation formulas for determining the magnitude and sign of the maximum tangential stresses in the meshing zone of the teeth with the greatest slippage, which are consistent with the results of finite element modeling, have been suggested.

References

1. Voroncov B., Dolja A. Pidvishhennja stijkosti ta poverhnevoї tverdosti zubchastih kolis ionnim azotuvannjam. *Materiali Mizhnarodnoї naukovo-praktichnoї internet-konferencії «Tendencії ta perspektivi rozvitku nauki i osviti v umovah globalizacії»:* Zb. nauk. prac'. Perejaslav, 2019. Vip. 52. S. 426-428

2. Gasanov M.I., Klochko O.O., Zakovorotnij O.Ju., Perminov Є.V. Tehnologichnij reglament optimizacії sistem vidnovlennja funkcional'nih vlastivostej velikogabaritnih vidkritih zubchatih peredach. *Visnik Nacional'nogo tehnichnogo universitetu «HPI». Serija: Tehnologії v mashinobuduvanni (Bulletin of the National Technical University «KhPI». Series: Techniques in a machine industry):* zb. nauk. pr.: Nacional'nij tehnichnij universitet «Harkivs'kij politehnichnij institut». Harkiv : NTU «HPI», 2018. № 6 (1282) 2018. S. 107–112.

3. Imitacijne modeljuvannja v zadachah mashinobudivnogo virobnictva: navch. pos. / za red. O. M. Shelkovogo. – Harkiv : NTU «HPI», 2019. 500 s. http://library.kpi.kharkov.ua/files/imitaciyne_modelyuvannya.pdf

4. Vasil'єva O.E., Chaliї D.O., Pridatko O.V. Analiz metodiv pokrashhennja roboti zubchastih peredach reduktoriv zagal'nogo priznachennja. *Materiali III vseukraїns'koї*

naukovo-praktichnoї internet-konferencії «Suchasnist'. nauka, chas. Vzaєmodija ta vzaєmovpliv». Kiїv, 22-24 listopada 2007. S. 64-67.

5. Klimenko O.D., Muravinec' Ju.V., Puc' V.S. Pidvishhennja nadijnosti zubchastih peredach. Naukovi notatki. 2022. №. 74. S. 140-144. https://doi.org/10.36910/775.24153966.2022.74.23

6. Casaroli A., Boniardi M., Conrado E. et al.Mechanical and metallurgical characterization of contact fatigue mechanisms in ADI spur gears. *Engineering Failure Analysis*. 2024. Vol. 165. 108775. https://doi.org/10.1016/j.engfailanal.2024.108775

7. Aulin V., Lysenko S., Grinkiv A. et al. Stress-strain State of the Surface Layer of Parts During the Implementation of Tribotechnical Running-in and Recovery Technologies. *Central'noukraïns'kij naukovij visnik: Tehnichni nauki*. 2019. № 1 (32). C.103-113. https://doi.org/10.32515/2664-262X.2019.1(32).103-113

8. Aulin V. V. Tribofizichni osnovi pidvishhennja znosostijkosti detalej ta robochih organiv sil's'kogospodars'koї tehniki: dis. d-ra. tehn. nauk : 05.02.04 / KNTU. Kirovograd, 2014. 447 s.

9. Suh N. P. The delamination theory of wear. *Wear*. 1973. Vol. 25, Is. 1. P. 111-124. https://doi.org/10.1016/0043-1648(73)90125-7

10. Aulin V.V., Grin'kiv A.V., Lisenko S.V., Livic'kij O.M., Babij A.V. Zakonomirnosti vplivu visokomodul'nih napovnjuvachiv na rozpodil poliv napruzhen' v poverhnevih sharah detalej mashin, vigotovlenih z polimernih kompozitnih materialiv. *Central'noukraïns'kij naukovij visnik. Tehnichni nauki.* 2022. Vip. 5(36)_I. S. 55-70. https://doi.org/10.32515/2664-262X.2022.5(36).I.55-70

11. Marchenko D., Matvyeyeva K. Study of the Stress-Strain State of the Surface Layer During the Strengthening Treatment of Parts. *Problems of Tribology*. 2022. 27(3/105). P. 82–88. https://doi.org/10.31891/2079-1372-2022-105-3-82-88

12. Lyashenko I. Description of the Stationary Structural States of a Boundary Lubricant Making Use of the Relation between the Density-Modulation and Excess-Volume Order Parameters. *Ukrainian Journal of Physics*. 2021. 66(11), 993. https://doi.org/10.15407/ujpe66.11.993

13. Lyashenko I. A., Filippov A. E., Popov M., Popov V. L. Effect of stress nonhomogeneity on the shear melting of a thin boundary lubrication layer. *Physical Review E*. 2016. 94, 5. P. 053002. https://doi.org/10.1103/PhysRevE.94.053002

14. Vasil'ev A.Ju., Grabovskij A.V., Martynenko A.V. ta in. Sopostavlenie raschetov kontaktnyh naprjazhenij v zubchatom zaceplenii po formule Gerca i metodom konechnyh jelementov. *Vestnik Nac. tehn. un-ta "HPI" : sb. nauch. tr. Temat. vyp. : Problemy mehanicheskogo privoda*. 2012. № 36. S. 20-24. https://repository.kpi.kharkov.ua/handle/KhPI-Press/10579.

15. Hussein A.W., Abdullah M.Q. Experimental stress analysis of enhanced sliding contact spur gears using transmission photoelasticity and a numerical approach, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 2023. 237. P. 4316-4336. DOI: 10.1177/09544062231152158

16. Dolan T.J. Influence of certain variables on the stresses in gear teeth. *J. Appl. Phys.* 1941. 12. P.584-591. DOI:10.1063/1.1712943

17. Toman A. A., Abdullah M. Q. An analytical approach for predicting the fillet and contact stresses in symmetric and asymmetric spur gears under frictional mesh assumptions. *Results in Engineering*. 2024. Vol. 23. P. 102391. https://doi.org/10.1016/j.rineng.2024.102391

18. Mikosianchyk O. O., Pedan Y. V., Mnatsakanov R. G. et al. Analysis of models and methods for assessing the strength characteristics of polymer composite materials. *Problems of friction and wear*. 2023. 3 (100). C.15-29. https://doi.org/10.18372/0370-2197.3(100).17891

Стаття надійшла до редакції 11.02.2025.

Oksana Mikosianchyk - Doctor of Technical Sciences, Professor, Head of the Department of Applied Mechanics and Materials Engineering, State University "Kyiv Aviation Institute", 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: oksana.mikos@ukr.net, https://orcid.org/0000-0002-2438-1333

Olha Ilina – graduate student of the Department of Applied Mechanics and Materials Engineering, State University "Kyiv Aviation Institute", 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, тел.: +38 044 406 77 70, E-mail: ilivna19930@gmail.com, https://orcid.org/0000-0002-1674-0578

Rudolf Mnatsakanov – Doctor of Technical Sciences, Professor, Professor of Aircraft Continuing Airworthiness Department, State University "Kyiv Aviation Institute", 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: mnatsakanov@ukr.net, https://orcid.org/0000-0001-5035-2432

Bespalov Sergii Anatolyevich - Doc. Tech. Sci., Senior Researcher, Scientific Secretary of the Sector of Physical, Technical and Mathematical Sciences of the Scientific and Organizational Department of the Presidium of the National Academy of Sciences of Ukraine, st. Volodymyrska, 54, Kyiv, Ukraine, 02000, tel.: +380442396444, E-mail: bespalov@nas.gov.ua, https://orcid.org/0000-0002-6664-8614

Olesia Yashchuk – Senior Lecturer at the Department of Professional Foreign Languages, State University "Kyiv Aviation Institute", 1 Lubomyra Huzar Ave., Kyiv, Ukraine, 03058, E-mail: olesya.yashchuk@gmail.com , https://orcid.org/0009-0000-6712-3804

Oleksii Kushch – Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Manufacturing, Repairing and Materials Science, National Transport University, Omelyanovicha-Pavlenka street 1, office 11, Ukraine, Kyiv 01010, E-mail: kushch_oleksiy@bigmir.net, https://orcid.org/0000-0001-7147-9803

О. МІКОСЯНЧИК, О. ІЛЬЇНА, Р. МНАЦАКАНОВ, С. БЕСПАЛОВ, О. ЯЩУК, О. КУЩ

АНАЛІЗ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ЗУБЧАСТОГО ЗАЧЕПЛЕННЯ ШЕСТЕРЕННОГО НАСОСУ В ПРОГРАМНОМУ КОМПЛЕКСІ ANSYS

Метою роботи була оцінка напружено-деформованого стану в зоні зачеплення зубців при терті при моделюванні зубчатого зачеплення шестеренного насосу в ANSYS Workbench. Встановлено, що при збільшенні контактного напруження за Герцем з 180 до 555 МПа глибина зони розподілу еквівалентних напружень по Мізесу та глибина локалізації максимальних еквівалентних напружень по Мізесу зростає на 20% та 23% відповідно. Аналіз епюр дотичних напружень (τ_{xy}) у поперечному перерізі зубців свідчить, що в зоні контакту дотичні напруження змінюються за величиною та знаком. Епюри мають два екстремуми, причому, величина максимальних напружень на випереджаючій поверхні (початковій головці зуба шестерні) приблизно на 10-15% нижче напружень на відстаючій поверхні (початковій ніжці зубця колеса). Встановлено високі розбіжності в визначенні максимальних дотичних напружень в симуляційній моделі зубчастого зачеплення в умовах кочення з проковзуванням за формулою Беляєва та при моделюванні. Запропоновано розрахункові формули визначення величини і знаку максимальних дотичних напружень в зоні зачеплення зубців з найбільшим проковзуванням, які узгоджуються з результатами моделювання методом скінченних елементів.

Ключові слова: моделювання, зубчасте зачеплення, напружено-деформований стан, шестеренний насос.

Список літератури

1. Воронцов Б., Доля А. Підвищення стійкості та поверхневої твердості зубчастих коліс іонним азотуванням. *Матеріали Міжнародної науково-практичної інтернет-конференції «Тенденції та перспективи розвитку науки і освіти в умовах глобалізації»*: Зб. наук. праць. Переяслав, 2019. Вип. 52. С. 426-428.

2. Гасанов М.І., Клочко О.О., Заковоротний О.Ю., Пермінов Є.В. Технологічний регламент оптимізації систем відновлення функціональних властивостей великогабаритних відкритих зубчатих передач. *Вісник Національного технічного університету «ХПІ». Серія: Технології в машинобудуванні (Bulletin of the National Technical University «KhPI». Series: Techniques in a machine industry)*: зб. наук. пр.: Національний технічний університет «Харківський політехнічний інститут». Харків : НТУ «ХПІ», 2018. № 6 (1282) 2018. С. 107–112.

3. Імітаційне моделювання в задачах машинобудівного виробництва: навч. пос. / за ред. О. М. Шелкового. – Харків : НТУ «ХПІ», 2019. 500 с. http://library.kpi.kharkov.ua/files/imitaciyne_modelyuvannya.pdf

4. Васильєва О.Е., Чалий Д.О., Придатко О.В. Аналіз методів покращення роботи зубчастих передач редукторів загального призначення. *Матеріали III всеукраїнської науково-практичної інтернет-конференції «Сучасність. наука, час. Взаємодія та взаємовплив»*. Київ, 22-24 листопада 2007. С. 64-67.

5. Клименко О.Д., Муравинець Ю.В., Пуць В.С. Підвищення надійності зубчастих передач. *Наукові нотатки.* 2022. №. 74. С. 140-144. https://doi.org/10.36910/775.24153966.2022.74.23

6. Casaroli A., Boniardi M., Conrado E. et al.Mechanical and metallurgical characterization of contact fatigue mechanisms in ADI spur gears. *Engineering Failure Analysis*. 2024. Vol. 165. 108775. https://doi.org/10.1016/j.engfailanal.2024.108775

7. Аулін В.В., Лисенко С.В., Гриньків А.В. та ін. Напружено-деформований стан поверхневого шару деталей при реалізації триботехнологій припрацювання і відновлення. *Центральноукраїнський науковий вісник: Технічні науки*. 2019. № 1 (32). С.103-113. https://doi.org/10.32515/2664-262X.2019.1(32).103-113

8. Аулін В. В. Трибофізичні основи підвищення зносостійкості деталей та робочих органів сільськогосподарської техніки: дис. д-ра. техн. наук : 05.02.04 / КНТУ. Кіровоград, 2014. 447 с.

9. Suh N. P. The delamination theory of wear. *Wear*. 1973. Vol. 25, Is. 1. P. 111-124. https://doi.org/10.1016/0043-1648(73)90125-7

10. Аулін В.В., Гриньків А.В., Лисенко С.В., Лівіцький О.М., Бабій А.В. Закономірності впливу високомодульних наповнювачів на розподіл полів напружень в поверхневих шарах деталей машин, виготовлених з полімерних композитних матеріалів. *Центральноукраїнський науковий вісник. Технічні науки*. 2022. Вип. 5(36)_I. С. 55-70. https://doi.org/10.32515/2664-262X.2022.5(36).I.55-70

11. Marchenko D., Matvyeyeva K. Study of the Stress-Strain State of the Surface Layer During the Strengthening Treatment of Parts. *Problems of Tribology*. 2022. 27(3/105). P. 82–88. https://doi.org/10.31891/2079-1372-2022-105-3-82-88

12. Lyashenko I. Description of the Stationary Structural States of a Boundary Lubricant Making Use of the Relation between the Density-Modulation and Excess-Volume Order Parameters. *Ukrainian Journal of Physics*. 2021. 66(11), 993. https://doi.org/10.15407/ujpe66.11.993

13. Lyashenko I. A., Filippov A. E., Popov M., Popov V. L. Effect of stress nonhomogeneity on the shear melting of a thin boundary lubrication layer. *Physical Review E*. 2016. 94, 5. P. 053002. https://doi.org/10.1103/PhysRevE.94.053002

14. Васильев А.Ю., Грабовский А.В., Мартыненко А.В. и др. Сопоставление расчетов контактных напряжений в зубчатом зацеплении по формуле Герца и методом конечных элементов. *Вестник Нац. техн. ун-та "ХПИ" : сб. науч. тр. Темат. вып. : Проблемы механического привода*. 2012. № 36. С. 20-24. https://repository.kpi.kharkov.ua/handle/KhPI-Press/10579.

15. Hussein A.W., Abdullah M.Q. Experimental stress analysis of enhanced sliding contact spur gears using transmission photoelasticity and a numerical approach, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 2023. 237. P. 4316-4336. DOI: 10.1177/09544062231152158

16. Dolan T.J. Influence of certain variables on the stresses in gear teeth. *J. Appl. Phys*. 1941. 12. P.584-591. DOI:10.1063/1.1712943

17. Toman A. A., Abdullah M. Q. An analytical approach for predicting the fillet and contact stresses in symmetric and asymmetric spur gears under frictional mesh assumptions. *Results in Engineering*. 2024. Vol. 23. P. 102391. https://doi.org/10.1016/j.rineng.2024.102391

18. Мікосянчик О. О., Педан Є. В., Мнацаканов Р. Г. та ін. Аналіз моделей та методів оцінки міцністних характеристик полімерних композиційних матеріалів. *Проблеми тертя та зношування (Problems of friction and wear)*. 2023. 3 (100). С.15-29. https://doi.org/10.18372/0370-2197.3(100).17891

Мікосянчик Оксана Олександрівна – докт. техн. наук, професор, завідувач кафедри прикладної механіки та інженерії матеріалів, Державний університет «Київський авіаційний інститут», пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел.: +38 044 406 77 70, E-mail: oksana.mikos@ukr.net, https://orcid.org/0000-0002-2438-1333

Ільїна Ольга Андріївна – аспірант кафедри прикладної механіки та інженерії матеріалів, Державний університет «Київський авіаційний інститут», пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел.: +38 044 406 77 70, E-mail: ilivna19930@gmail.com, https://orcid.org/0000-0002-1674-0578

Мнацаканов Рудольф Георгійович – докт. техн. наук, професор, професор кафедри підтримання льотної придатності повітряних суден, Державний університет «Київський авіаційний інститут», пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел.: +38 044 406 76 70, Email: mnatsakanov@ukr.net, https://orcid.org/0000-0001-5035-2432 .

Беспалов Сергій Анатолійович - док. техн. наук, старший науковий співробітник, учений секретар сектору фізико-технічних і математичних наук науково-організаційного відділу Президії НАН України, вул. Володимирська, 54, м. Київ, Україна, 02000, тел.: +380442396444, E-mail: bespalov@nas.gov.ua, https://orcid.org/0000-0002-6664-8614

Ящук Олеся Петрівна – старший викладач кафедри іноземних мов професійного спрямування, Державний університет «Київський авіаційний інститут», пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел.: +38 044 406 76 70, Email: olesya.yashchuk@gmail.com , https://orcid.org/0009-0000-6712-3804

Кущ Олексій Іванович – канд. техн. наук, доцент, доцент кафедри «Виробництво, ремонт та матеріалознавство», Національний транспортний університет, вулиця Омеляновича-Павленка 1, кабінет 11, Київ, Україна, 01010, E-mail: kushch_oleksiy@bigmir.net, https://orcid.org/0000-0001-7147-9803