MECSOL 2022 - Proceedings of the 8th International Symposium on Solid Mechanics
M.L. Bittencourt, J. Labaki, L.C.M. Vieira Jr. and E. Mesquita (Editors), Campinas SP, Brazil, October 17th to 19th, 2022

APPLYING SURFACE CONTACT ON STRUCTURES ASSESSMENT

Ion Willer Dos Santos[1] and Jánes Landre Júnior[1]
[1] Pontifical Catholic University of Minas Gerais. Av. Dom José Gaspar, 500, Coração Eucarístico, MG, Brasil, 30535-901

In dynamic systems surface contact between moving parts is present. In systems like these, gears transfer power from engines; wheels, are supported on rails, and so on. Since it is necessary to occur friction and tension arise between parts in contact, in a uncertain moment systems will fail due to overload on surfaces, or due to loss of strength of materials. In this article it will be presented different applications of concepts concerning surface contact on dynamic systems, in order to assess its condition on certain time. In the end it will be concluded on the effective use of such proposals on designing products and predicting devices failure.
Keywords: Structure reliability, fatigue failure, surface contact, condition based maintenance

INTRODUCTION

Companies nowadays need to face a rough market with competitors quite qualified. Besides that, they need to compete in a globalized world. Thus challenges arised to them: shorter production cycles, better quality products, faster processes than usual, assets better used on a lifetime and so on.

In a scenario like this, systems must last as much as possible in order to ensure the better ROI (Return Of investment). It means that once an equipment starts running, its cycle of operation must be as long as possible, without failing. More over, even under some damage it must still work.

For goods production dynamic systems are applied. In order to them to work as designed, surface contacts occurs. This paper will present and discuss researches analyzing situations where surface contacts can be identified. Further more, different papers will be introduced in order to show how different applications imply on treating failures as surface contact stress.

Contact stress analysis: an overview

As a premise it can be taken for granted that surface contact stress is unavoidable in dynamic systems. From the papers listed here we see it is present on analysis of contacts between materials, manufacturing processes, going through tools materials and so on.

In order to organize the articles they will be sorted based upon main areas on structure assessment and complementary areas.

Forces analysis

Allamraju, K. V. (2019) analyze Aluminium Alloys (AA), since they are having poor solidification in micro structure and porosity in weld region. AA3003 alloy is used as reference and its Mechanical properties are presented by taking five samples along with contact stress analysis between pin and side wall of the AA3003-H12 during dwelling stage. AA3003 can be formed into sheet, plate, foiled, extruded into rod, bar, wired and forged. In order to get a better joining Friction Stir Welding (FSW) is applied for being the best suitable and novel method. Figures 1 and 2 present stresses obtained on experiments.

As conclusion, it is found that sample 2 gave optimum strength in comparison to other samples. Besides that, contact stress is taken as very aspect in order to determine the axial force for friction stir welding.

As conclusion it was figured out that welding speed plays important role in increasing the tensile strength of FSW welded joint as well as contact stress plays important role to determine the axial force for plunging.

Hertz contact stress calculation

A calculation of Hertz contact stress between the deep groove ball bearing and inner race using analytical and MESYS tool analysis is presented by R., A. P., Babu, V. S. and K., V. A. (2018). The calculation procedure consists of calculating maximum contact pressure at different loads using analytical formulas. Besides that, comparison of results with MESYS

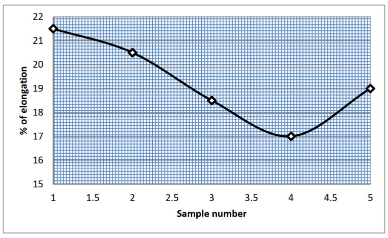


Figure 1 – Variation of percentage of elongation in relation to samples. Extracted from Allamraju, K. V. (2019)

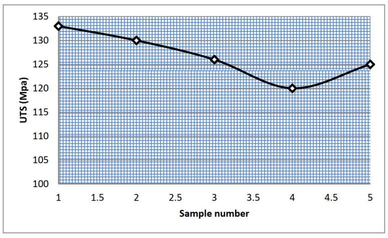


Figure 2 – Variation of ultimate tensile strength (UTS) in relation to samples. Extracted from Allamraju, K. V. (2019)

tool to predict the contact pressure between inner race and ball of single row deep groove ball bearing is conducted. The contact between inner race and ball is considered as an elliptical contact.

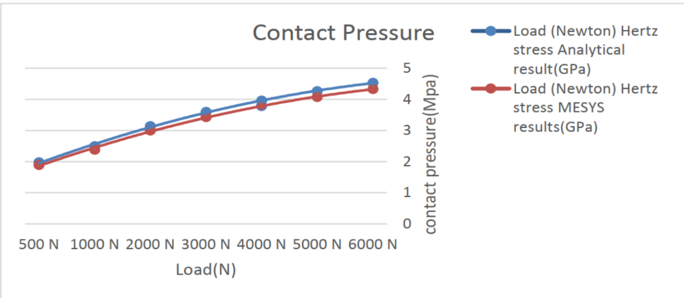


Figure 3 – Comparison of experimental and theoretical results. Extracted from R., A. P., Babu, V. S. and K., V. A. (2018)

It is concluded from the result it is clear that the variation of MESYS result to that of formulated result is very less, that is, less than 5%.

In Wen, Q., Du, Q. and Zhai, X. (2019) Spur gears with tip relief can effectively improve transmission performance, and accurate determination of their tooth surface contact stress (TSCS) can provide guidance for structure optimization and performance evaluation. However, since the tip-relieved gear profile has not been accurately approximated with a quadratic parabola, the TSCS cannot be calculated using the cylindrical contact model of the Hertzian contact theory (Hertz model). Therefore, a new more accurate analytical model for calculating the non-Hertzian TSCS of tip-relieved gears is proposed in this paper. This model is established based on the accurate tooth profile equations represented by the parameter equations (new model). The solution of the model with an implicit function and a singular integral is also studied. Finally, the TSCS of two gear pairs with and without tip relief are compared for different parameters under different loads according to the new model, the finite element method (FEM model) and Hertz model. The results show that the tip relief will affect the maximum TSCS, location and size of the contact area, whereas the Hertz model cannot quantify these effects. However, the new model, which is validated using the FEM model, can provide accurate and reliable results.

The results show that for the TSCS calculation of the involute gear without tip relief, the quadratic curve equation in the Hertz model can closely approximate the involute curve. Therefore, the results of the Hertz models are consistent with those of the new and FEM models. As shown in Fig. 4, the results of the new model are in good agreement with those of the FEM model under different exponents of the tip-relieved curve.

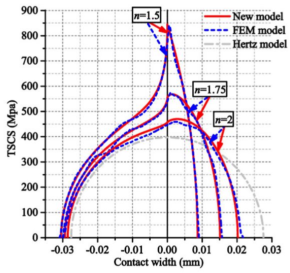


Figure 4 – The experimental results of contact stress under different loads. Extracted from Wen, Q., Du, Q. and Zhai, X. (2019)

In Wen, Q., Du, Q. and Zhai, X. (2020) it is discussed problems concerning misalignment errors (MEs) in multiple degrees of freedom (multi-DOFs) along gear pair axis are unavoidable under actual working conditions. These MEs lead to changes in tooth surface contact stress (TSCS) and make its accurate calculation complicated and difficult. Unlike the traditional methods of obtaining TSCS with MEs in multi-DOFs via experimental tests, finite element methods (FEMs) or coefficient methods following international stan- dards, a new analytical calculation model is proposed in this paper. The profile equation of a gear pair with MEs in multi-DOFs is first established. Then, a new profile equation for meshing pairs of gear and pinion slices with non-standard shapes that are coplanar with the line of action of the meshing force is obtained. On this basis, the correctness of meshing force transmission, as well as the accuracy and speed of calculation, can be guaranteed with the contact analysis of gear pairs. Finally, the magnitude and distribution of the TSCS of a gear pair with MEs in multi-DOFs are obtained. It is shown by Fig. 5 the effectiveness of new model.

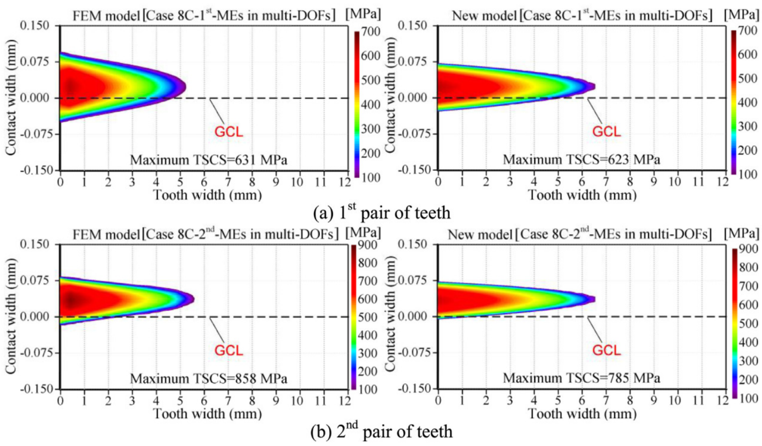


Figure 5 – The experimental results of contact stress under different loads. Extracted from Wen, Q., Du, Q. and Zhai, X. (2020)

Compared with the results of a FEM model, the new model can accurately and rapidly calculate the TSCS of a gear pair with MEs in multi-DOFs.

Contact mechanics analysis

Photoelasticity has always played an important role in the experimental study of contact mechanics. It can with a degree of simplicity be used to measure the parameters that characterize the contact stress field. The so-called over-deterministic method is the most widely used in that regard. Although that particular method functions correctly, it has some metrological limitations: no measurement uncertainties are provided; observations are assumed to be independent and of equal accuracy; and its results may be skewed by the misalignment of the coordinate axes in the data collection. Fernández, M. S. (2019) discusses the use of Generalized Least Squares by Lagrange Multipliers method. This one can override those limitations. The application of the method is illustrated by an example, which shows its potential. The method provides not only an estimate of the quantities to be measured, as the over-deterministic method, but also: a fitted estimate of the value of each input quantity, the covariance matrix of all these estimates from which both the standard uncertainties and the correlation coefficients can be calculated, a chi-square value that can be used to test the consistency of the measurement model, and the normalized deviations between the input estimates and their fitted values, which are a tool to identify potential outliers. Fig. 6 shows fringes obtained on study.

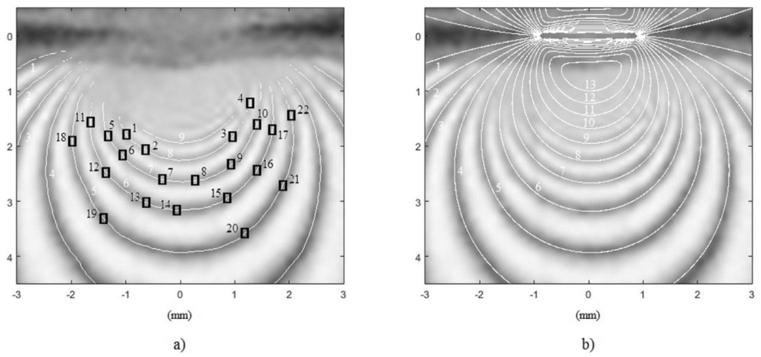


Figure 6 – a) Experimental isochromatics with the fringe skeletons and data points superimposed; b) theoretically reconstructed fringes over the experimental isochromatics. Extracted from Fernández, M. S. (2019)

The consistency test has led to the acceptance of the measurement model and no outliers have been found. The estimates and associated standard uncertainties of input quantities have been corrected, and correlation coefficients between all quantities involved in the measurement process have been calculated.

Prediction of contact stress

In Gudmundson, and Larsson (2021) explicit expressions for stress–strain relationships and swelling strains are derived for porous lithium-ion electrodes. Local contact stresses between neighboring electrode particles are also predicted. The analytical model is based on similar microstructural averaging techniques that previously have been applied to simulations of powder compaction. Both direct particle–particle and particle–binder–particle contacts are considered. The model gives explicit dependencies of constituent material properties and parameters describing the microstructure geometry. Examples are presented for electrodes that have particle–particle contacts below the percolation limit. The prediction of the E-modulus shows good agreement with experimental results. Constrained swelling resulting from intercalation of lithium-ions has also been simulated. Schematic sketch of three spherical particles of radius R with one particle–particle contact and one particle–binder–particle contact is shown by Fig.7.

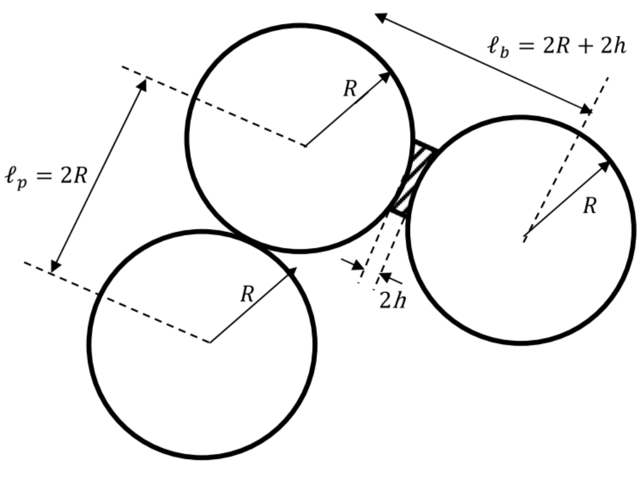


Figure 7 – Schematic sketch of three spherical particles of radius R with one particle–particle contact and one particle–binder–particle contact. Extracted from Gudmundson, and Larsson (2021)

The resulting electrode stress state compares well with numerical predictions by the finite element and the discrete element method. Local particle–particle contact stresses of the order 1–6 GPa have as well been predicted. A simplified model using a model for rigid-plastic deformation of particles have shown that the stress–strain behavior during the first charging cycle may substantially differ from subsequent cycles, a phenomenon that also has been experimentally observed.

Contact features analysis

Liu, J., Li, X. and Shi, Z. (2020) investigate the contact characteristics of the bearings with the subsurface crack, which may be helpful for the incipient fault detection. A main failure mode of the roller bearings is the subsurface crack due to the contact fatigue, which can produce large spalling. To overcome this problem, this study presents a finite element model to study the effects of the horizontal and slant subsurface cracks on the contact characteristics in a roller bearing. The relationship between the contact deformation and crack sizes (length, depth, and slope angle) is obtained, as well as that between the contact zone width and crack sizes. The mathematical relationship between the contact characteristics and crack sizes is obtained by using a polynomial fitting approach. Note that the crack length, depth, and slope angle will affect the contact characteristics of the bearing.

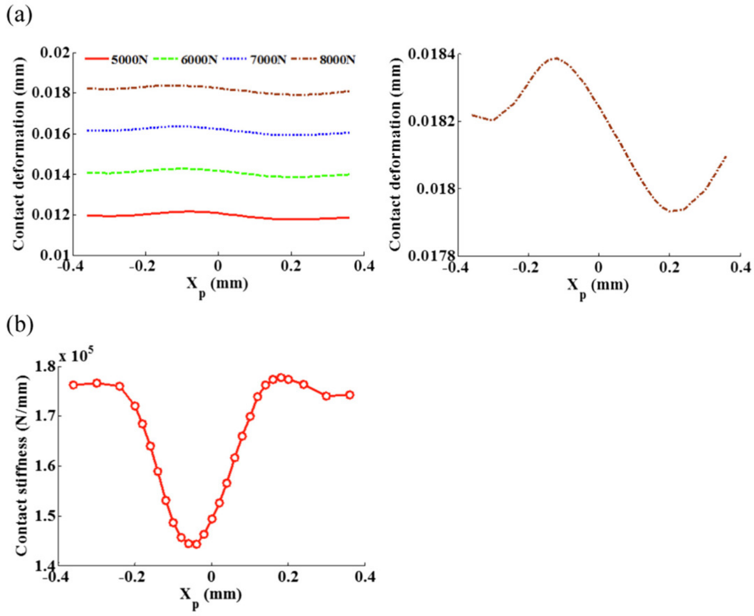


Figure 8 – The effect of the horizontal subsurface crack on the time-varying (a) contact deformation and (b) contact stiffness. Extracted from Liu, J., Li, X. and Shi, Z. (2020)

The results provide that the established approach can give a useful numerical method for analyzing the contact characteristics of a roller bearing with the horizontal and slant subsurface cracks (v. Fig. 8).

Degradation prediction

In Lu, C. (2022) a simulation methodology with the combination of finite element modeling, Archard theory, and Arbitrary Lagrangian-Eulerian (ALE) technique is proposed for the accumulated wear degradation prediction of railway friction block. The validation is conducted with a test bench from the perspectives of tribological and dynamic behaviors during the running-in and formal testing processes. The friction pair comprises a forged steel brake disc and a Cu-based powder metallurgy friction block.

The results indicate that the contact area increases during the running-in process and the average contact pressure decreases first and then fluctuates around a stable value, v. Fig 9. In the formal testing process, although the accumulated wear mass and the wear mass per cycle increase with the number of braking cycles, the increase rate of friction block wear mass decreases rapidly in the first few cycles and then decreases slowly. The prediction error of the proposed method for the accumulated wear mass is less than 5%. The research in this work is helpful to have a deep understanding of the wear degradation mechanism of friction block and can provide an effective method for the prediction of friction block wear degradation.

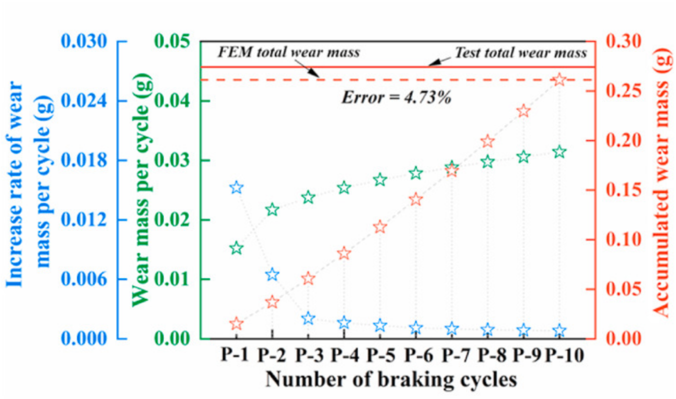


Figure 9 – The effect of the horizontal subsurface crack on the time-varying (a) contact deformation and (b) contact stiffness. Extracted from Lu, C. (2022)

Contact stress as a leading parameter on designs

Mehta et al. (2018) say that the contact stress in the mating gears is the key parameter in gear design. Deformation of the gear is also another key parameter which is to be considered. Gears generally fail when the working stress exceeds the maximum stress. The study in this paper shows that the complex design problem of spur gear which requires fine software skill for modeling and also for analyzing. The project aims at the minimization of both contact stress as well as deformation to arrive at the best possible combination of driver and driven gear. In this process comparison of Von Mises Stress, Strain and Total Deformation was done of a ceramic (Silicon Nitride) with a conventional steel gear as a substitute in the gear manufacturing industry and the software programmed was performed in SOLIDWORKS and ANSYS Workbench to get the best result possible.

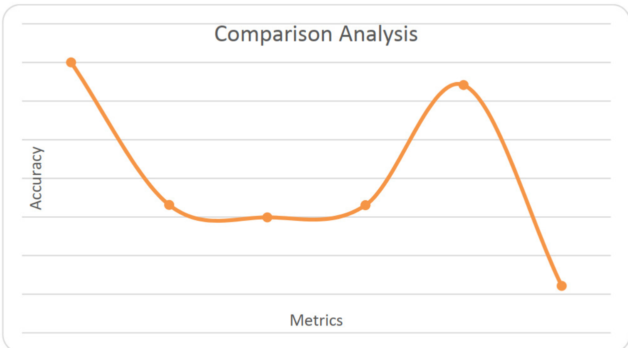
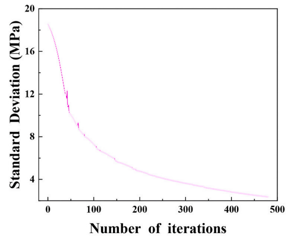


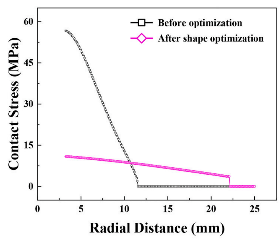
Figure 10 – Comparison Graph between Metrics. Extracted from Mehta et al. (2018)

From result simulations it has been seen that Silicon nitride yields better results i.e comparative stress and reduced strain and strain energy with respect to conventional steel. Silicon Nitride Manufactured gears also experience less deformations, contributing to greater work life, v. Fig. 10.

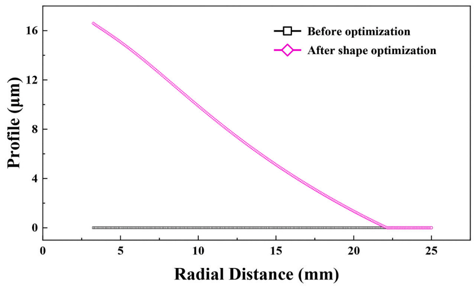
Zhou, Y., Lin, Q., Hong, J. and Yang, N. (2021), An investigation into the material stiffness design for enhancing the uniformity of the contact stress is conducted in this paper. A bidirectional evolutionary optimization design approach for interface material stiffness is developed, in which the standard deviation of the contact stress is defined as the objective function and the Young's modulus is treated as the design variable. A design case of a single bolted joint verifies that the proposed bidirectional material stiffness optimization approach can effectively improve the uniformity of the contact stress. A region-averaging treatment is proposed as the post-processing of the optimized Young's modulus distribution to make the optimized structure more manufacturable. The capabilities for homogenizing the contact stress distribution with various geometry sizes are addressed. A comparison study with the interface shape optimization indicates that with nearly the same improvement of the standard deviation of the contact stress, the material stiffness design around the contact region is more effective on enlarging the effective contact area and is much more computationally efficient than the interface shape optimization. Iteration history of the standard deviation, contact stress distribution and profile of the contact surface graphics can be seen in Fig. 11.



(a) Iteration history of the standard deviation



(b) Contact stress distribution



(c) Profile of the contact surface

Figure 11 – Results of the interface shape optimization. Extracted from Zhou, Y., Lin, Q., Hong, J. and Yang, N. (2021)

A common single bolted joint design case is investigated and the standard deviation of the contact stress is reduced by nearly one order of magnitude with only 19 optimization iteration steps needed, which reveals the effectiveness of the proposed bidirectional material stiffness optimization approach. For the optimized continuous Young's modulus distribution with low-resolution, a simple region-averaging treatment is proposed as the post-processing. Only two discrete Young's modulus are used to make the optimized structure more manufacturable. Moreover, it is found that the proposed approach is capable of optimizing the contact stress distribution with various geometry sizes.

Contact stress effect on moving parts

In Neisi, N. et al. (2018) Contact stresses of a ball bearing type touchdown bearing with off-sized balls are studied. The touchdown bearing model includes descriptions of the stiffness, damping and friction between bearing components. The model gives the contact deformations between the balls and bearing races, contact forces, and Hertzian contact stresses in each ball. The bearing model is used in simulation together with a model of a flexible rotor. Maximum Hertzian stress in specific balls is shown in Fig. 12.

The results show that offsized ball or balls alters the contact stiffness between the balls and bearing race and the localized deformation of race. The contact force and stresses consequently change. The stress values are dependent not only on the dimension of the off-sized ball or balls but also their location.

Dynamic systems analysis

Selection of the contact force model plays a crucial role in the modeling and analysis of dynamical systems. The seminal work by Hunt and Crossley, published in 1975, is one of the most prominent contact force models that finds application in different areas of science and engineering. The contact force approach proposed by Hunt and Crossley has motivated and inspired a large number of researchers that, eventually, led to the publication of numerous solutions to evaluate contact forces. Silva, M. R. et al. (2022) present an extensive collection of contact force models available in the literature that have been developed on the basis of the Hunt and Crossley's cornerstone work. The behavior of each contact force model is assessed with a simple example of application and their performance is analyzed. Figure 13 shows the relation between the post and pre-restitution coefficients for the different contact force models

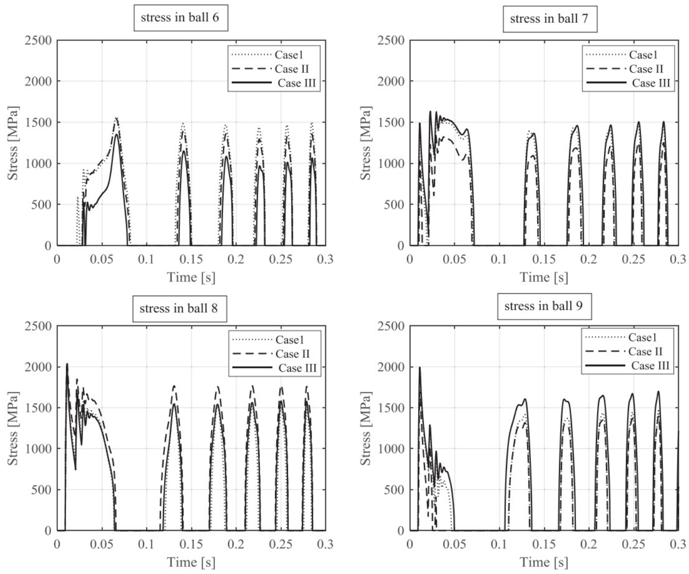


Figure 12 – Maximum Hertzian stress in balls 6, 7, 8 and 9. Case I: without off-sized ball, Case II: single off-sized ball (ball 8), Case III: multiple off-sized balls (ball 7, 8, 9). Extracted from Neisi, N. et al. (2018)

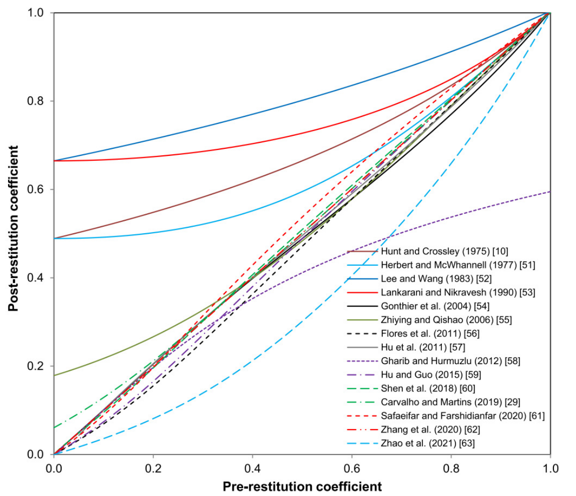


Figure 13 – Relation between the post and pre-restitution coefficients for the different contact force models. Extracted from Silva, M. R. et al. (2022)

By analyzing the diagrams constructed for all models, it can be concluded that the choice of the contact force model and associated parameters must be carefully considered when modelling contact-impact scenarios, as the shape of the diagrams is strongly affected by the value chosen for the coefficient of restitution and the diagrams notably differ amongst models. When comparing all fifteen contact force models, it can be concluded that there is a tendency for the most recent models to be suitable for the entire range of the coefficient of restitution.

Material performance and behavior

Studying the instability of cutting force and production of high-frequency stress impact on the cutting tool due to vibration caused by segmented chip, Wang, T. et al. (2021) present a new new impact test method considering contact stress. The segmented chip morphology and contact stress between chip and flank face of coated cutting tool were studied by cutting experiments. It was found that the average contact stress of the coated tool was 4.9 GPa and the alternating frequency reached 22 kHz. A new high-frequency impact test method was used to simulate the loading condition of coated tools in the cutting experiments. Figure 14 shows the wear morphology of two kinds of coated tools after turning Ti-6Al-4V (f = 0.2 mm/rev).

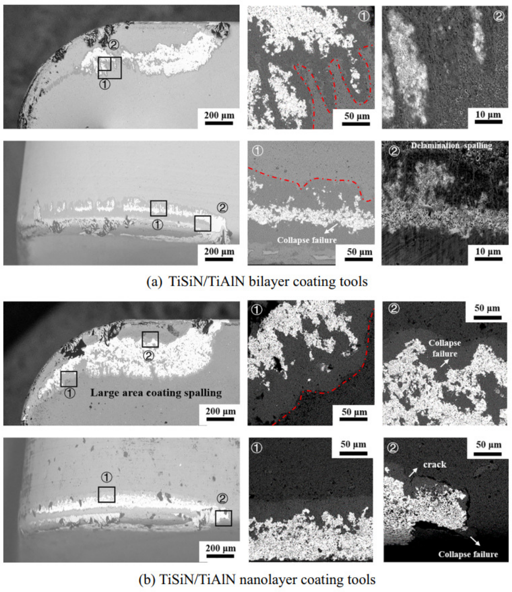


Figure 14 – The wear morphology of two kinds of coated tools after turning Ti-6Al-4V. Extracted from Wang, T. et al. (2021)

Results showed that the cutting performance of the coated tool was related to the impact fatigue resistance. In the case of a high feed rate (above 0.1 mm/rev) or high preloading depth (7.51 μm and 9 μm), TiSiN/TiAlN bilayer coating shows better performance, compared with TiSiN/TiAlN nanolayer coating. However, in the case of low feed rate (less than 0.1 mm/rev) or low preloading depth (18 μm), TiSiN/TiAlN nanolayer coating shows better performance. Cutting conditions and coating structure could match to get optimized cutting performance of coated cutting tools.

CONCLUSIONS

This paper relates to surface contact stress researches. Different situations were analyzed from several papers found. In overview we can consider two main areas: product design or structural reliability. References presented can be classified into one area or another, or even in both of them. Anyway proposals are useful on designing or condition prediction.

For designing products it is important to be able to predict parts operational conditions and behavior. Thus, forces analysis, Hertz contact stress calculation, contact mechanics analysis, contact features analysis, contact stress as a leading parameter on designs, contact stress effect on moving parts and dynamic systems analysis can be applied to create better products, concerning its lifetime.

In the other hand, structural reliability will apply concepts found on sections such as prediction of contact stress, degradation prediction and material performance and behavior. Those concepts can be used as a reliable source of parameters to supervise parts condition changing through time.

As formerly said some of the topics can be applied on both areas, such as contact stress effect on moving parts and material performance and behavior.

As final consideration, from this work it can be seen how widely surface contact stress can be applied.

ACKNOWLEDGMENTS

We would like to thank Vale S.A. and Pontifical Catholic University of Minas Gerais for supporting this research.

REFERENCES

Allamraju, K. V., 2019, "Mechanical Properties and Contact Stress analysis between Pin and Sidewall of AA3003 during Dwelling by using FSW", J. Materials Today: Proceedings, Vol. 18, pp 3643-3650.

Allamraju, K. V., Poojitha, E. and Rasagnya, G., 2021, "Contact stress analysis of metallic and additive manufacturing material in transmission", J. Materials Today: Proceedings, Vol. 44, 573-578.

Cao, Y, Liu, C., Tian, H., Zhang, S. and Sun, Y., 2020, "Prediction of the driving force for a cup pig based on the distribution of contact stress", Journal of Natural Gas Science and Engineering ,Vol. 81, art. 103415.

Gudmundson, P.,Larsson, P., 2021, "An analytic model for effective mechanical properties and local contact stresses in lithium-ion porous electrodes", J. Extreme Mechanics Letters, Vol.42, 101967.

Fernández, M. S., 2019, "Metrological considerations in the measurement of contact stress parameters using photoelasticity", J. Optics and Lasers in Engineering, Vol. 117, pp 29-39.

Liu, J., Li, X. and Shi, Z., 2020, "An investigation of contact characteristics of a roller bearing with a subsurface crack", J. Engineering Failure Analysis, Vol. 116, art. 104744.

Liu, J., Feng, H. and Zhou, C., 2022, "Static load distribution and axial static contact stiffness of a preloaded double-nut ball screw considering geometric errors", J. Mechanism and Machine Theory, Vol. 167, art. 104460.

Liu, T., Yu, Q., Fan, J., Peng, Z. and Wang, 2021, E. "Concrete spherical joint contact stress distribution and overturning moment of swing bridge", J. Structures, Vol. 28, pp 1187-1195.

Lu, C., Yin, J., Mo, J. and Wang, J., 2022, "Accumulated wear degradation prediction of railway friction block considering the evolution of contact status", International Journal of the Science and Technology of friction Lubrication and Wear, 494-495, art. 204251.

Mahdavi, H., Poulios, K. and Niordson, C. F., 2020, "Effect of superimposed compressive stresses on rolling contact fatigue initiation at hard and soft inclusions", International Journal of Fatigue, Vol. 134, art. 105399

Mahdavi, H., Poulios, K., Kadin, Y. and Niordson, C. F. ,2022, "On the effect of microplasticity on crack initiation from subsurface defects in rolling contact fatigue", International Journal of Fatigue, Vol. 161, 106870.

Mandal, N. K., Spiryiagin, M., Wu, Q., Wen, Z. and Stichel, S., 2022, "FEA of mechanical behaviour of insulated rail joints due to vertical cyclic wheel loadings", J. Engineering Failure Analysis, Vol. 133, art. 105966.

Mehta, G., Somani, M., Babu, N. and Watts, T., 2018, "Contact Stress Analysis on Composite Spur Gear using Finite Element Method, ", J. Materials Today: Proceedings, 2018, Vol. 5, 13585-13592.

Neisi, N., Sikanen, E., Heikkinen, J. E. and Sopanen, J., 2018, "Effect of off-sized balls on contact stresses in a touchdown bearing", J. Tribology International, Vol. 120, pp 340-349.

Silva, M. R., Marques, F., Silva, M. T. and Flores, P., 2022, "A compendium of contact force models inspired by Hunt and Crossley's cornerstone work", J. Mechanism and Machine Theory, Vol. 167, art. 104501.

Sugunesh, A.P., Mertens, A. J., (2021), "2D FEA study of Hertzian contact stress between two cylindrical bodies", J. Materials Today: Proceedings, Vol. 44, 4474-4478.

Wang, S., Yao, X. F., Yang, H. and Huang, S. H., 2019, "Measurement and evaluation on contact stress at the rubber contact interface", J. Measurement, Vol. 146, pp 856-867.

Wang, T., Zha, X., Chen, F., Wang, J., Lin, L., Xie, H., Lin, F. and Jiang F., 2021, "Research on cutting performance of coated cutting tools by a new impact test method considering contact stress condition caused by segmented chips", J. of Manufacturing Processes, Vol. 68, 1569-1584.

Wang, Y., Zou, B., Huang, C., Qi, H. and Song, J., 2019, "Feasibility study of the Ti(C 7 N 3)-based cermet micro-mill based on dynamic fatigue behavior and modeling of the contact stress distribution on the round cutting edge", J. International Journal of Mechanical Sciences, Vol. 155, pp 143-158

Wen, Q., Du, Q. and Zhai, X., 2020, "Analytical calculation of the tooth surface contact stress of spur gear pairs with misalignment errors in multiple degrees of freedom", J. Mechanism and Machine Theory, Vol. 149, art. 103823

Zhang, B., Liu, H., Quiñonez, A. F. and Venner, C. H., 2020, "Effects of 3D anisotropic heterogeneous subsurface topology on film thickness, pressure, and subsurface stresses in an elasto-hydrodynamically lubricated point contact", J. Tribology International, Vol. 151, 106471.

Zhou, Y., Lin, Q., Hong, J. and Yang, N., 2021, "Bidirectional evolutionary optimization design of material stiffness for the uniformity of the contact stress", J. European Journal of Mechanics / A Solids, Vol.89,art.104288.

Zhou, L., Bai, W., Han, Z., Wang, W., Hu, Y., Ding, H., Lewis, R., Meli, E., Liu, Q. and Guo, J., 2022, "Comparison of the damage and microstructure evolution of eutectoid and hypereutectoid rail steels under a rolling-sliding contact", International Journal of the Science and Technology of friction Lubrication and Wear, art. 204233.

RESPONSIBILITY NOTICE

The authors are the only parties responsible for the printed material included in this paper.