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DOI: 10.18421/TEM141-29

| abstract | full text | how to cite |

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DOI: 10.18421/TEM141-30

| abstract | full text | how to cite |

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Authors: Sirinthra Sungthong, Kanokwan Meesook, Somnuk Aujirapongpan, Charoenchai Agmapisarn, Tanakrit Yordudom

DOI: 10.18421/TEM141-31

| abstract | full text | how to cite |

Title: *Empower Employee Development: The Role of Self-Study Materials in Work-Based Learning*

Authors: Vasilii Ostin

DOI: 10.18421/TEM141-32

| abstract | full text | how to cite |

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| abstract | full text | how to cite |

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Authors: Muhammad Bukhori Dalimunthe, Rosmala Dewi, Haryadi Haryadi, Agung Haryono, Bagus Shandy Narmaditya

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| abstract | full text | how to cite |

Title: *Mapping the Landscape of Risk Management in Islamic Banking: A Bibliometric Exploration*

Authors: Muhamad Subhi Apriantoro, Anggraini Arum Mawarti, Fina Nusa Puspa

DOI: 10.18421/TEM141-35

| abstract | full text | how to cite |

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Authors: Viera Tomková

DOI: 10.18421/TEM141-36

| abstract | full text | how to cite |

Title: *Deep Learning-Based Generalized Efficient Layer Aggregation Network for the Detection of Coal Trucks*

Authors: Ade Oktarino, Alanoud Subahi, Nouf Atiahallah Alghanmi, Andi Besse Firdausiah Mansur, Andi Tenriawaru, Ahmad Hoirul Basori

DOI: 10.18421/TEM141-37

| abstract | full text | how to cite |

Title: *The Impact of Higher Education in Transition Students-Graduates in Socio Economic Level and Employment: Colombian Case*

Authors: Jorge Moreno-Gomez, Evaristo Navarro-Manotas, Lesly Silvera-Hernandez, Giovanny Misat-Gomez

DOI: 10.18421/TEM141-38

| abstract | full text | how to cite |

Title: *Development of TPACK-LK (Technological Pedagogical and Content Knowledge with Learner Knowledge) Instrument for Mathematic Preservice Teacher*

Authors: Mohammad Auza'i Aqib, Rooselyna Ekawati, Siti Khabibah

DOI: 10.18421/TEM141-39

| abstract | full text | how to cite |

Title: *Simulation and Experimental of PSMEID with Preview for Controlling Shock Vibration on UAV's Landing Gear*

Authors: Darmawan Darmawan, Lovelyson Lovelyson, Meifal Rusli, Rahmadi Kurnia

DOI: 10.18421/TEM141-40

| abstract | full text | how to cite |

Title: *K-12 STEM Teachers' Experiences with Artificial Intelligence*

Authors: Antoine Azzam, Tendai Charles

DOI: 10.18421/TEM141-41

| abstract | full text | how to cite |

Title: *Design Strategy of Indonesian Robotic Visual Programing Language for Pre-School Children*

Authors: Mara Nugraha, Eri Prasetyo Wibowo, I Made Wiryana

DOI: 10.18421/TEM141-42

| abstract | full text | how to cite |

Title: *Leveling of Critical Thinking Abilities of Junior High School Students in Solving Geometry Problems*

Authors: Ari Suningsih, I Ketut Budayasa, Ismail Ismail

DOI: 10.18421/TEM141-43

| abstract | full text | how to cite |

Title: *Bridging Motivation and Mastery: The Role of Self-Efficacy in Math Education*

Authors: Amjad Islam Amjad, Muhammad Abid Malik, Sarfraz Aslam, Musarrat Habib

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| abstract | full text | how to cite |

Title: *An Investigation into ChatGPT-Enhanced Adaptive E-learning Systems*

Authors: Mohammad T. Alshammari

DOI: 10.18421/TEM141-45

| abstract | full text | how to cite |

Title: *A Performance-Driven Exploration of Combining Topic Modeling and Machine Learning for Online Learning Data Analysis*

Authors: Pachisa Kulkanjanapiban, Tipawan Silwattananusarn

DOI: 10.18421/TEM141-46

| abstract | full text | how to cite |

Title: *Influence of Higher Education on IoT Acceptance through Hands-On Learning*

Authors: José Varela-Aldás, Christian Junta, Elias Choque, Guillermo Palacios-Navarro

DOI: 10.18421/TEM141-47

| abstract | full text | how to cite |

Title: *Enhancing Student Success in Engineering Programs through the Innovative Teaching Model*

Authors: Mária Mišútová, Martin Mišút

DOI: 10.18421/TEM141-48

| abstract | full text | how to cite |

Title: *Digital Technology in Classroom Assessment: A Bibliometric Study*

Authors: Najdah Sanusi, Hafizhah Zulkifli, Mohd Isa Hamzah

DOI: 10.18421/TEM141-49

| abstract | full text | how to cite |

Title: *Determining Factors Sustainable Competitive Advantage in Private Higher Education*

Authors: Elistia Elistia, Dedi Purwana, Mohammad Sofwan Effendi, Muhtosim Arief, Setyo Ferry Wibowo

DOI: 10.18421/TEM141-50

| abstract | full text | how to cite |

Title: *Development of Syntactic Complexity in Saudi EFL Male Undergraduates' Writings in the Light of Using Telegram*

Authors: Lamyaa Falah AlMohaya, Talal Musaed Alghizzi, Sameer Mohammed Dandan

DOI: 10.18421/TEM141-51

| abstract | full text | how to cite |

Title: *Virtual Reality-Based or Assisted Learning and Academic Achievement: A Meta-Analytic Review*

Authors: Ulfia Rahmi, Yullys Helsa, Suparman Suparman, Winanda Amilia, Azrul Azrul

DOI: 10.18421/TEM141-52

| abstract | full text | how to cite |

Title: *Project-Based Learning Combined with Inquiry-Based Learning Using Solver Tools to Promote Computational Thinking Among Undergraduate Students*

Authors: Narongsak Sangpom, Wasukree Sangpom

DOI: 10.18421/TEM141-53

| abstract | full text | how to cite |

Title: *Impact of Gamification on Teaching-Learning Criminal Law: A Quasi-Experimental Study with University Students*

Authors: Yasmina Beatriz Riega-Virú, Alfonso Renato Vargas-Murillo, Ilda Nadia Monica de la Asuncion Pari-Bedoya

DOI: 10.18421/TEM141-54

| abstract | full text | how to cite |

Title: *Developing Research Competence in Prospective Lecturers of Building Engineering Education through Research-Based Blended Flip Learning (RBBFL) Model*

Authors: Sri Sumarni, Muhammad Akhyar, Muhammad Nizam, Herry Widyastono

DOI: 10.18421/TEM141-55

| abstract | full text | how to cite |

Title: *Exploring the Future of Education: Integrating Metaverse and AI Tools to Enhance Learning Experiences*

Authors: Petr Svoboda, Ladislava Knihová

DOI: 10.18421/TEM141-56

| abstract | full text | how to cite |

Title: *Connected Creative Problem Solving: An Alternative Integrative Learning Model Based on Thinking Skills*

Authors: Rusmini Rusmini, Suyono Suyono, Rudiana Agustini, Amiq Fikriyati

DOI: 10.18421/TEM141-57

| abstract | full text | how to cite |

Title: *Research Publication on Virtual Reality in Early Childhood Education: A Systematic Review*

Authors: Kartika Rinakit Adhe, Muchamad Arif Al Ardha, Herawati Herawati, Sauqi Sawa Bikalawan, Gunarti Dwi Lestari, Chung Bing Yang

DOI: 10.18421/TEM141-58

| abstract | full text | how to cite |

Title: *Comparative Analysis of Gifted Education in Denmark and the USA With a Focus on the State of Iowa*

Authors: Antonia Ćurić, Danijela Blanuša Trošelj, Andrea Debeljuh

DOI: 10.18421/TEM141-59

| abstract | full text | how to cite |

Title: *A Bibliometric Analysis of the Development of Artificial Intelligence (AI) Research in Education in Scopus Indexed Journals: What are the Future Trends of this Research?*

Authors: Muhammad Turmuzi, Ratna Yulis Tyaningsih

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| abstract | full text | how to cite |

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Authors: Iis Marwan, Nia Rohayati

DOI: 10.18421/TEM141-61

| abstract | full text | how to cite |

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Authors: Milena Stefanova, Tihomir Stefanov, Silviya Varbanova, Boni Bonev

DOI: 10.18421/TEM141-62

| abstract | full text | how to cite |

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DOI: 10.18421/TEM141-63

| abstract | full text | how to cite |

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Authors: Marco Antonio Rodríguez Vega, María del Pilar Castro Arellano, Eliana Maritza Barturen Mondragón, Guillermo Alexander Quezada Castro, María del Pilar Quezada Castro

DOI: 10.18421/TEM141-64

| abstract | full text | how to cite |

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| abstract | full text | how to cite |

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DOI: 10.18421/TEM141-66

| abstract | full text | how to cite |

Title: *Exploring Video Lecture Effectiveness for Elementary STEM Education: Instructor Presence, Video Quality, and Student Perceptions*

Authors: Nguyen Thi Phuong Nhung, Pham Thi Huong

DOI: 10.18421/TEM141-67

| abstract | full text | how to cite |

Title: *A Novel Algorithm for Differentiating Authorized Users from Fraudsters via Mobile Keypad Input Patterns During Password Updates*

Authors: Boumedyen Shannaq

DOI: 10.18421/TEM141-68

| abstract | full text | how to cite |

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Authors: Petra Furdi Šafarić, Anica Hunjet, Dijana Vuković

DOI: 10.18421/TEM141-69

| abstract | full text | how to cite |

Title: *AI-Enabled Adaptive E-Learning Systems Adoption in Conflict Zone: Case Study of Palestinian Schools*

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DOI: 10.18421/TEM141-70

| abstract | full text | how to cite |

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Authors: Bexi Perdomo, Carlos Pérez Pérez

DOI: 10.18421/TEM141-71

| abstract | full text | how to cite |

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| abstract | full text | how to cite |

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| abstract | full text | how to cite |

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| abstract | full text | how to cite |

Title: *PISA Content Quantity-Standardized Test: Exploring Vocational Student's Mathematical Communication Skills*

Authors: Nurcholif Diah Sri Lestari, Mohammad Najih, Inge Wiliandani Setya Putri, Wasilatul Murtafiah, Faridah Hanim Yahya, Suwarno Suwarno

DOI: 10.18421/TEM141-75

| abstract | full text | how to cite |

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DOI: 10.18421/TEM141-76

| abstract | full text | how to cite |

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| abstract | full text | how to cite |

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| abstract | full text | how to cite |

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| abstract | full text | how to cite |

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DOI: 10.18421/TEM141-80

| abstract | full text | how to cite |

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DOI: 10.18421/TEM141-81

| abstract | full text | how to cite |

Title: *Taguchi's Method for Optimum Cutting of Acrylic Materials on a 40-Watt CNC Laser Cutting Machine*

Authors: Yatin Ngadiyono, Dimas Ari Saputra, Bayu Rahmat Setiadi, Pardjono Pardjono

DOI: 10.18421/TEM141-82

| abstract | full text | how to cite |

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| abstract | full text | how to cite |

Title: *Computational Thinking in Mathematics Instruction Integrated to STEAM Education: A Systematic Review and Meta-Analysis*

Authors: Suparman Suparman, Dadang Juandi, Turmudi Turmudi, Bambang Avip Priatna Martadiputra, Yullys Helsa, Masniladevi Masniladevi, Dea Stivani Suherman

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| abstract | full text | how to cite |

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| abstract | full text | how to cite |

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Numerical Study of Rim Thickness Effects on Tooth Root Stress in Metal-Composite Gears

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***Abstract* – Hybrid metal-composite gears, which combine the strengths of traditional metal gears with advanced composite materials, have become a promising solution for various industrial applications. This study presents a comprehensive numerical analysis of the influence of rim thickness on tooth root stress in metal-composite gears. In the process of manufacturing composite gears, the gear body is replaced with a composite, excluding the hub and rim, which remain metallic. This analysis includes proportional scaling of the rim thickness while keeping other parameters constant to assess its impact on root stress distribution. Six different cases are examined. In each case, various gear configurations are considered, starting from a fully metal gear and moving to hybrid metal-composite gears with varying rim thicknesses. Ansys Workbench is used for the analysis, and the results are verified with analytical calculations according to ISO 6336-3. This study establishes a deeper understanding of the compromise between rim thickness and stress distribution. The conclusions gained from this study can guide gear engineers in optimizing the design of hybrid metal-composite gears.**

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1. Introduction

Gears are crucial mechanical components for power transmission because of their consistent transmission ratios and high load-bearing capabilities. Various types of gears exist but, cylindrical gears with either straight or oblique teeth are among the most common. The main difference between these gears is that the teeth of the spur gears are aligned parallel to the axis of rotation, whereas in helical gears, the teeth are angled at β. Helical gears, compared to spur gears, can bear higher loads and operate more quietly. In spur gears, contact between the teeth occurs all at once across the entire width of the gear. In contrast, in helical gears, contact begins at one point on the tooth edge and gradually extends across the whole tooth, aiding in a quieter gear operation [1], [2], [3], [4].

The increasing need to reduce the weight of load-bearing parts, especially in the automotive and aviation industries, has increased the need for the development of innovative technological solutions for components composed of multiple materials. With this, different characteristics can be obtained in different segments of the part using a material for a specific application. For example, metal parts can be added to a composite part to improve assembly operations. In addition, combining multiple materials in one part can lead to a significant reduction in weight without impairing the functional characteristics of the part. The use of composite materials, together with metals, in a hybrid structure is currently being developed for application in high-tech industries [14]. In the aviation industry, a combination of composites and aluminum is used in the latest aircraft models. The same thing happens in the military industry, for example, in the ships of the US Navy, certain structures can be found that are composed of metal and composite.

By combining a composite material with a metal, a metal-composite hybrid structure can be obtained, which allows the grouping of the mechanical properties of both materials. This combination has great potential and is especially applicable when there is a need for mass reduction [5], [6].

The need to reduce mass also appears in gears. Several solutions for mass reduction can be found in the literature. Traditionally, the mass of gears is reduced by reducing the thickness of the ring and gear body. These studies were conducted by several authors [7], [8]. In addition, with new manufacturing technologies, such as 3D printing, mass reduction can also be achieved using different structures that cannot be obtained with traditional manufacturing methods. In previous work, the use of a lattice structure in gears, that is, reducing the mass while maintaining the characteristics of the gear in terms of carrying capacity, was investigated [9].

The application of hybrid gears in modern engineering represents a significant advance towards achieving high performance while reducing mass. These gears, which combine different materials, such as metals and composites in their construction, allow the optimization of mechanical properties for specific applications. For example, the gear body can be made of a lightweight composite material to reduce mass, while the teeth and hub are made of metal to improve durability and power transfer capability. This innovative use of hybrid materials not only contributes to efficiency and cost-effectiveness within various industries but also improves the operational characteristics of the systems where they are used. Recently, research in the field of hybrid gears has increased and become more popular. The authors in [10] and [13] are working on developing a model of hybrid gears, combining metal and composite, aiming to reduce the mass. The analyses were performed using the Finite Element Method (FEM) by performing a static analysis and comparing the performance of a hybrid gear with an all-metal gear. This study shows that with hybrid gears, a significant reduction in mass can be obtained, as well as an improvement in performance.

The influence of the geometrical parameters of hybrid gears on the stress, stiffness, and dynamic behavior was analyzed in [11]. The authors are working to optimize the performance by carefully selecting the geometrical parameters. Additionally, NASA has conducted research in this area. In [12], they developed and tested hybrid gears. Tested for more than 300 million cycles at high speeds and torques, hybrid gears have demonstrated success.

2. Methodology

To determine the impact of the gear rim thickness on the stress at the tooth root, six different cases were examined. In each case, various gear configurations were considered, starting from a fully metal gear and then moving to hybrid metal-composite gears with varying rim thicknesses (Figure 1). In the first case, a traditional, fully metal gear was analyzed, which serves as a baseline for comparing the results. The other analyzed gears are hybrid, meaning that the gear rim and hub are made of metal, while the body is made of a composite material, carbon fiber and resin. In these gears, the rim thickness is the only variable changed across different cases, whereas all other parameters remain unchanged to observe their influence on the stresses. The rim thickness S_R (Figure 1) is related to the module m, starting from 2.5m, down to 0.5m, decreasing by 0.5 for each case.

All gears were modelled using the SolidWorks software suite, and the stress analysis at the tooth root was conducted using structural analysis in the Ansys Workbench software. Table 1 lists the gear parameters. The metal gears are made from 16MnCr5 material, while for the hybrid gears, the metal part (the rim and hub) remains the same, and the body is made from a composite material named Epoxy Carbon Woven (395 GPa) prepreg, with characteristics taken from the Ansys database. Additionally, to validate the results of the structural analysis, an analytical calculation of the stress at the tooth root was conducted according to ISO 6336-3.

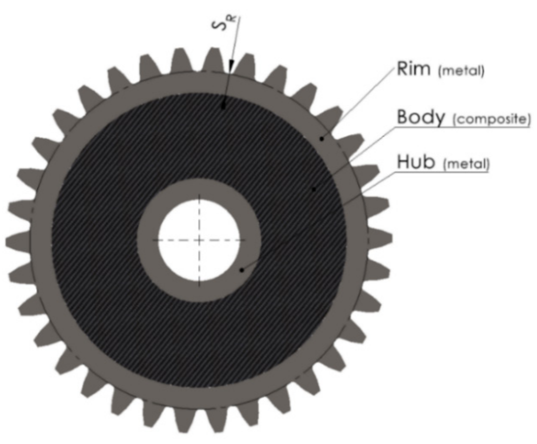

Figure 1. Hybrid metal-composite gear

3. Analytical Calculation of the Stress at the Tooth Root

The performance of gears largely depends on the stress distribution within the gear tooth, and particular attention should be paid to the stress at the tooth root. This stress can contribute to tooth failure. Understanding and accurately predicting this stress is a fundamental task in gear dimensioning.

The maximum stress at the tooth root can be determined by various methods, such as Finite Element Analysis (FEA), integral equations, or experimentally using strain gauge strips. In addition to these methods, according to ISO 6336-3 [16], [15] the nominal relevant loading at the tooth root is determined based on the force that loads the tooth at external point D (Figure 2).

Table 1. Gears parameters

Parameter	Pinion	Solid Gear	Hybrid gear (2,5m)	Hybrid gear (2m)	Hybrid gear (1,5m)	Hybrid gear (1m)	Hybrid gear (0,5m)
Number of teeth	*34*	*34*	*34*	*34*	*34*	*34*	*34*
Modul [mm]	*5*	*5*	*5*	*5*	*5*	*5*	*5*
Pressure angle [˚]	*20*	*20*	*20*	*20*	*20*	*20*	*20*
Pitch diameter [mm]	*170*	*170*	*170*	*170*	*170*	*170*	*170*
Face width [mm]	*25*	*25*	*25*	*25*	*25*	*25*	*25*
Rim thickness [mm]	*/*	*/*	*12,5*	*10*	*7,5*	*5*	*2,5*
Torque [Nm]				*339.15*			
Contact Force [N]				*3750*			

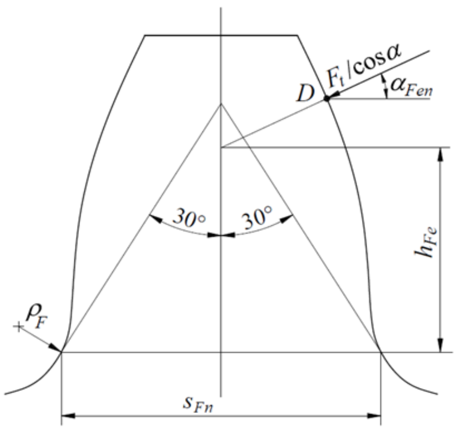

Figure 2. Tooth loading at external point D[17]

At this point, the entire load is transferred only by the current tooth. The formula for calculating the nominal stress according to ISO 6336-3 [16] is as follows:

$$\sigma_{F0} = \frac{F_t}{b * m_n} Y_F Y_S Y_\beta Y_B Y_{DT} \tag{1}$$

Where,

F_t- Contact force,
b- Face width.
m_n- Normal module,
Y_F - Tooth form factor, and can be calculated according to equation (2):

$$Y_F = \frac{6\left(\frac{h_{Fe}}{m_n}\right) * \cos\alpha_{Fen}}{\left(\frac{s_{Fn}^2}{m_n^2}\right) * \cos\alpha_n} \tag{2}$$

Where,

h_{Fe} - Bending moment arm for the tooth root stress (Figure 2),
s_{Fn} - Tooth root thickness at the critical section (Figure 2),
α_{Fen} - Load direction angle (Figure 2),
α_n – Pressure angle,

Y_S - stress correction factor, and can be calculated according to equation (3):

$$Y_S = (1.2 + 0.13 * L)q_s^{\left\{\frac{1}{\left[1.21+\left(\frac{2.3}{L}\right)\right]}\right\}} \quad (3)$$

Where,

$$L = \frac{S_{Fn}}{h_{Fe}} \quad (4)$$

$$q_s = \frac{S_{Fn}}{2 * \rho_F} \quad (5)$$

Where,

ρ_F - *Tooth root radius at the critical section*
Y_β - *Helix angle factor,*
Y_B - *Rim thickness factor, and*
Y_{DT} - *Deep tooth factor.*

Although the main method used in this study to determine the maximum stress at the tooth root is FEA, for the verification of the simulation, the calculated maximum stress for a solid gear will be used, with the individual parameters and conditions shown in Table 1. A detailed calculation was made using formulas (1) to (5), and is presented as follows:

$$\sigma_{F0} = \frac{F_t}{b * m_n} Y_F Y_S Y_\beta Y_B Y_{DT} = \frac{3750}{25 * 5} * 1.435 * 2.32 * 1 * 1 * 1 = 99.88\ MPa$$

$$F_t = 3750\ N$$

$$b = 25\ mm$$

$$m_n = 5\ mm$$

$$Y_F = \frac{6\left(\frac{h_{Fe}}{m_n}\right) * \cos\alpha_{Fen}}{\left(\frac{S_{Fn}^2}{m_n^2}\right) * \cos\alpha_n} = \frac{6\left(\frac{4.919}{5}\right) * \cos 19.04}{\left(\frac{10.170^2}{5^2}\right) * \cos 20} = 1.435$$

$$Y_S = (1.2 + 0.13 * L)q_s^{\left\{\frac{1}{\left[1.21+\left(\frac{2.3}{L}\right)\right]}\right\}} = (1.2 + 0.13 * 2.067)2.891^{\left\{\frac{1}{\left[1.21+\left(\frac{2.3}{2.067}\right)\right]}\right\}} = 2.32$$

$$L = \frac{S_{Fn}}{h_{Fe}} = \frac{10.170}{4.919} = 2.067$$

$$q_s = \frac{S_{Fn}}{2 * \rho_F} = \frac{10.170}{2 * 1.759} = 2.891$$

$$Y_\beta = 1$$

$$Y_B = 1$$

$$Y_{DT} = 1$$

Based on the presented calculation, a maximum stress at the tooth root for a full gear of 99.88 MPa was obtained.

4. Finite Element Analysis

As previously mentioned, FEA was used to determine the impact of the gear rim thickness on the tooth root stress. Six cases were analyzed: a solid gear, a hybrid gear, and rim thicknesses of 12.5, 10, 7.5, 5, and 2.5 mm. Figure 3 shows a gear pair in a mesh, where one gear is a test gear and changes for each case, whereas the other is solid and remains the same for all cases. The 3D models of the gears were prepared using the SolidWorks software package and then imported into Ansys Workbench.

Consistent boundary conditions were used for all analyses. Specifically, for the hybrid gears, a rigid connection was established between the gear body, rim, and hub (Figure 3). On surface A, a cylindrical support was defined with no degrees of freedom, and on surface B, a cylindrical support allowed for rotation. Additionally, a moment of 339150 *Nmm* was defined on surface B. The contact between the gears in mesh is defined as frictionless contact. Six analyses were conducted, and the stress values at the tooth root were recorded. The first case, that is, the analysis of a solid gear, which serves as a reference for the comparison of the results, is also the basis for the validation of the model with the analytical calculation.

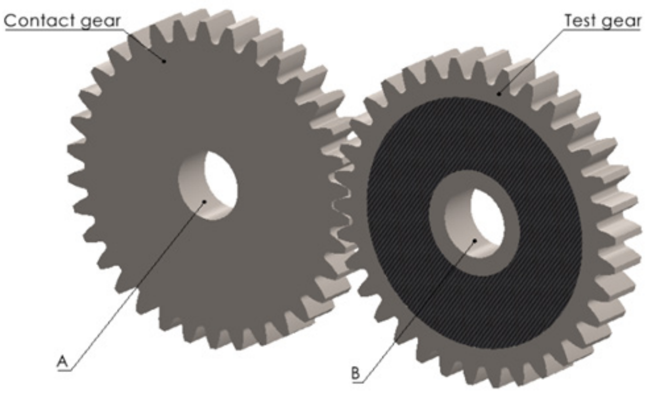

Figure 3. Meshing gears

A well-structured and defined mesh is of great importance for the model because the results largely depend on the mesh quality. Using the tools in Ansys Workbench for mesh control, the size of the elements is defined as 3 mm, while a finer mesh of 0.4 mm is specified for the contact surface and the root part of the tooth where the stresses are measured.

Prism-shaped elements are used because they converge the solution faster than tetrahedral-shaped elements. Figure 4 illustrates the meshing of the models.

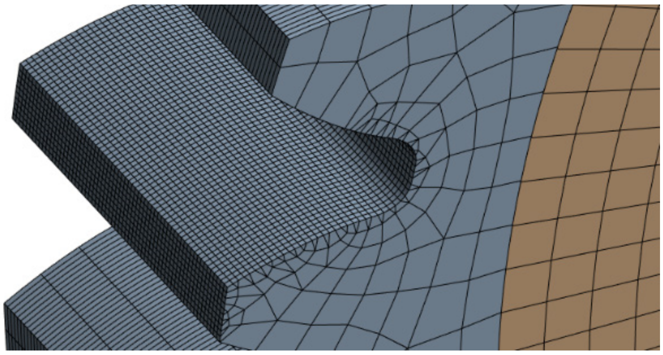

Figure 4. Meshed model of gear pair

5. Results and Discussion

From the analytical calculation performed for the stress at the tooth root, a result of 99.88 MPa was obtained and compared with the stress measured from Ansys Workbench for the first case, solid gears. In this case, a stress of 92.377 MPa was recorded, resulting in a difference of -7.5%. This discrepancy occurs because of the assumptions made in the analytical calculation. The results for all cases are shown in figures 5-10 for each case individually.

A group display of the results is shown in Figure 11. As expected, reducing the thickness of the gear rim increased the stress at the tooth root.

For the first cases, the difference was smaller. For a hybrid gear with a rim thickness of 12.5 mm, a stress of 97.53 MPa was recorded, corresponding to an increase in stress of 5%. For a rim thickness of 10 mm, a stress of 99.45 MPa was recorded, representing a difference of 7.65% compared to a full gear. For a rim thickness of 7.5 mm, the stress was 103.03 MPa, or a difference of 11.5%. For cases with a thin rim, namely thicknesses of 5 mm and 2.5 mm, a significant increase in stress is observed. A stress of 113.78 MPa was recorded for a rim thickness of 5 mm, and a stress of 139.24 MPa for a rim thickness of 2.5 mm, representing differences of 23.17% and 50.73%, respectively.

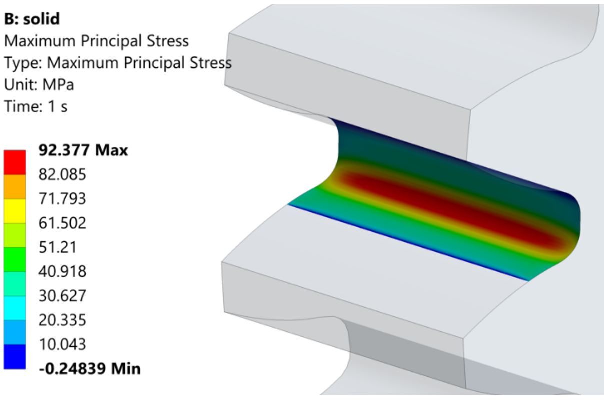

Figure 5. Root stress results for the solid gear

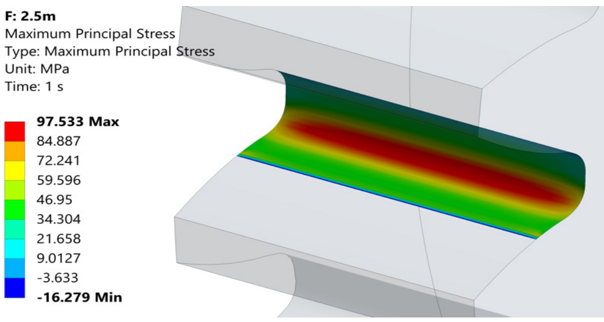

Figure 6. Root stress results for hybrid metal-composite gear with a rim thickness of 12.5 mm

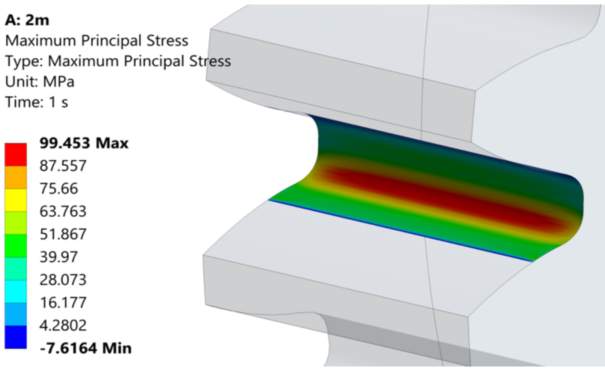

Figure 7. Root stress results for hybrid metal-composite gear with a rim thickness of 10 mm

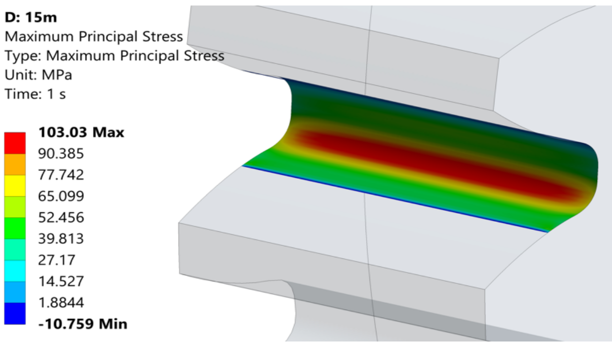

Figure 8. Root stress results for hybrid metal-composite gear with a rim thickness of 7.5 mm

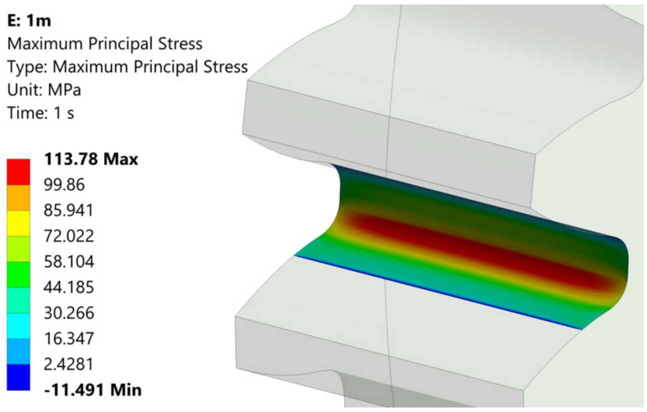

Figure 9. Root stress results for hybrid metal-composite gear with a rim thickness of 5 mm

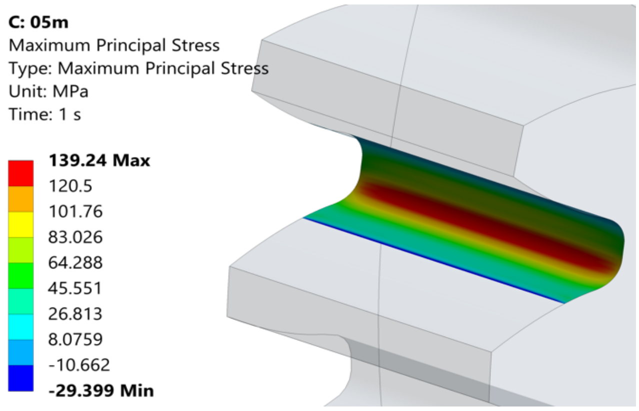

Figure 10. Root stress results for hybrid metal-composite gear with a rim thickness of 2.5 mm

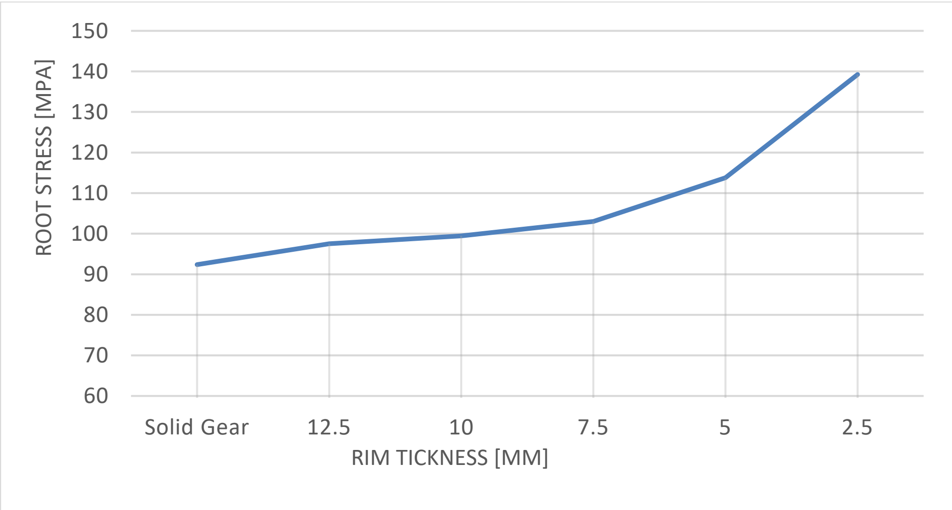

Figure 11. Comparison between the results

6. Conclusion

The analysis presented in this paper highlights the significance of rim thickness on the stress at the tooth root in hybrid metal-composite gears. It is clearly demonstrated that a thinner rim results in a significant increase in stress compared to a fully metal gear. This research underscores the importance of considering rim thickness when designing hybrid metal-composite gears to ensure optimal performance and durability.

This study focused solely on rim thickness; future research should be conducted to determine the optimal hub thickness and to explore the connection between the metal and composite materials. This would help to further refine the design and performance parameters for these types of gears.

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