MOBILITY & VEHICLE MECHANICS

https://doi.org/10.24874/mvm.2024.50.01.05

UDC: 629.3.018.4; 541.68

IMPACT OF MICROSTRUCTURED SURFACE ON THE FATIGUE PERFORMANCE OF POLYPROPYLENE SPECIMENS FOR ADVANCED HYDROGEN AUTOMOTIVE APPLICATIONS

Krisztián Kun [1], Adrián Bognár[2], Bence Molnár[3]*

Received in September 2024 *Accepted in October 2024*

RESEARCH ARTICLE

ABSTRACT: The automotive industry is increasingly focusing on lightweight and high-performance materials to meet stringent environmental and efficiency standards. Polymers play a pivotal role in this shift, as they offer design flexibility and significant weight reduction. Injection moulding is one of the most widely used manufacturing processes for producing high-quality plastic components in the automotive sector. A critical application area is in hydrogen fuel cell vehicles, where the integrity and durability of Type 4 hydrogen storage tanks depend on the strong adhesion between the polymer liner and the composite structure. Enhancing this bond is crucial to ensuring safety and performance under high-pressure conditions. By tailoring the surface microstructure of polymer liners through advanced injection moulding techniques, the adhesion to composite materials can be significantly improved. Despite the detailed mechanical properties provided in the technical data sheets of polymers, fatigue characteristics are often not included, even though many automotive plastic components are exposed to repetitive stresses during their operational life. This research aims to investigate the effect of microstructures created by modern manufacturing technology, which is currently undergoing significant development for automotive applications, particularly in relation to hydrogen technology.

KEY WORDS: *Fatigue, Microstructure, Femtosecond laser, Type 4*

[1]*Krisztián Kun, Department of Innovative Vehicles and Materials, GAMF Faculty of Mechanical Engineering and IT, John von Neumann University, H-6000 Kecskemét, Hungary; kun.krisztian@nje.hu, https://orcid.org/0000-0001-7194-3581 (*Corresponding author)*

[2]*Adrián Bognár, Department of Innovative Vehicles and Materials, GAMF Faculty of Mechanical Engineering and IT, John von Neumann University, H-6000 Kecskemét, Hungary; bognar.adrian@nje.hu,*

[3]*Bence Molnár, Department of Innovative Vehicles and Materials, GAMF Faculty of Mechanical Engineering and IT, John von Neumann University, H-6000 Kecskemét, Hungary; molnar.bence@nje.hu, https://orcid.org/0009-0001-8410-8814*

UTICAJ MIKROSTRUKTURISANE POVRŠINE NA OTPORNOST NA ZAMOR POLIPROPILENSKIH UZORAKA ZA NAPREDNE AUTOMOBILSKE PRIMENE U HIDROGENSKOJ TEHNOLOGIJI

REZIME: Automobilska industrija sve više se fokusira na lake materijale visokih performansi kako bi ispunila stroge standarde ekologije i efikasnosti. Polimeri igraju ključnu ulogu u ovoj tranziciji, jer omogućavaju fleksibilnost u dizajnu i značajno smanjenje težine. Brizganje plastike je jedan od najčešće korišćenih proizvodnih procesa za izradu visokokvalitetnih plastičnih komponenti u automobilskoj industriji. Ključna oblast primene je u vozilima sa vodoničnim gorivnim ćelijama, gde integritet i izdržljivost vodoničnih rezervoara tipa 4 zavise od jake adhezije između polimerne obloge (liner) i kompozitne strukture. Poboljšanje ove veze je presudno za obezbeđivanje bezbednosti i performansi u uslovima visokog pritiska. Prilagođavanjem mikrostrukture površine polimernih obloga primenom naprednih tehnika brizganja, adhezija sa kompozitnim materijalima može se značajno poboljšati. Iako tehnički podaci polimera obuhvataju detaljne mehaničke karakteristike, osobine zamora često nisu uključene, iako su mnoge plastične komponente u automobilima izložene ponavljajućim naprezanjima tokom svog radnog veka. Ova istraživanja imaju za cilj da ispitaju uticaj mikrostruktura stvorenih savremenim proizvodnim tehnologijama, koje trenutno prolaze kroz značajan razvoj za primene u automobilskoj industriji, posebno u vezi sa vodoničnom tehnologijom.

KLJUČNE REČI: *Zamor, mikrostruktura, femtosekundni laser, tip 4*

IMPACT OF MICROSTRUCTURED SURFACE ON THE FATIGUE PERFORMANCE OF POLYPROPYLENE SPECIMENS FOR ADVANCED HYDROGEN AUTOMOTIVE APPLICATIONS

Krisztián Kun, Adrián Bognár, Bence Molnár

INTRODUCTION

The automotive industry is undergoing a transformative shift towards sustainable and efficient energy solutions, with hydrogen technology emerging as a key player in the pursuit of zero-emission vehicles [1-3]. Hydrogen fuel cells offer a promising alternative to traditional combustion engines and battery-electric vehicles, providing high energy density and rapid refuelling capabilities [4-6]. However, the successful integration of hydrogen technology in automotive applications is heavily dependent on the development of reliable and durable storage systems, such as Type 4 hydrogen tanks (**Figure 1**), which utilize a polymer liner reinforced with composite materials. Kis et al. (2023) emphasized the importance of strong adhesion between the polymer liner and the composite shell to prevent structural failures under high-pressure conditions [7]. Surface modifications at the microstructural level have been shown to significantly enhance the mechanical interlocking and adhesion properties of polymer composites. Berczeli (2018) demonstrated that advanced surface modification techniques could improve the adhesion strength between polymers and composite materials, making them suitable for high-stress environments like hydrogen storage systems [8]. Furthermore, Weltsch and colleagues, in their 2023 study, found that femtosecond laser ablation can precisely control the microstructure of the polymer surface, optimizing the interface between the liner and the composite. This approach not only enhances adhesion but also contributes to improved fatigue resistance [9]. Fatigue performance is a critical factor in the long-term reliability of polymer components in automotive applications. S. Mortazavian et al. highlighted that while the mechanical properties of polymers are well-documented, their fatigue characteristics are often neglected [10]. This oversight is particularly significant in automotive applications where parts are exposed to repetitive stresses, such as in hydrogen storage systems. Ahmadifar et al., in their publication, pointed out that understanding the fatigue behaviour of polymer components is essential for ensuring the safety and durability of hydrogen-powered vehicles [11].

This study aims to build on the existing body of research by investigating the effect of microstructured surfaces on the fatigue behaviour of polypropylene specimens, a widely used polymer in automotive applications. By examining different microstructural configurations and their impact on mechanical properties, this research seeks to provide insights into the optimization of polymer components for advanced hydrogen automotive applications.

Figure 1. A Type 4 tank (JEC World 2022) - own photo.

1. MATERIALS AND METHODS

The rapid expansion of plastics in various fields, particularly in automotive and aerospace industries, is notable. Despite their growing use, our understanding of the material characteristics of polymers is less comprehensive compared to metals. Engineering plastics are well-defined in terms of properties like tensile strength, elongation, and Young's modulus. However, their resistance to cyclic loading, or fatigue behavior, is less explored. This is especially critical as many plastic components are subjected to repetitive mechanical stress during their service life, impacting their longevity and performance. Consequently, accurate and reliable methods to determine these characteristics are essential for modern research. Fatigue in polymers involves cyclic stresses that are often below the material's yield strength, leading to failure over time. These failures can be classified into low-cycle fatigue, characterized by a combination of elastic and plastic deformation, and high-cycle fatigue, which occurs under primarily elastic conditions. Unlike metals, which exhibit a constant modulus of elasticity within their elastic limit, polymers demonstrate higher internal damping and lower thermal conductivity. This results in significant heating of the specimen under cyclic loading, even at low frequencies. The increase in temperature can cause a reduction in modulus, affecting the material's mechanical properties and performance. Moreover, polymers, especially in additive manufacturing [12],[13] do not have a well-defined fatigue limit as seen in metals. Instead, fatigue testing for polymers is typically conducted up to a certain number of cycles - often 10^7 cycles - to determine the corresponding stress levels under specific conditions like frequency, temperature, and humidity. Despite this, comprehensive and standardized methods for assessing fatigue behavior in polymers are lacking. Current practices primarily rely on data provided by material manufacturers, with limited empirical validation. As a result, there is a pressing need for systematic and thorough research to develop reliable fatigue characterization methods for polymers, particularly for applications that require high mechanical performance under cyclic loading [14]. Addressing this knowledge gap is crucial for advancing the use of polymers in critical applications, such as automotive components and hydrogen storage systems, where reliable material performance is essential. Establishing robust testing methods and understanding the underlying mechanisms of polymer fatigue will enable the development of more durable and efficient components, meeting the increasing demands of modern engineering applications. [11]

For this research, a special injection moulding tool was used, which produces two standard bending test specimens. Our goal was to create microstructures on the surface of the stationary mould insert that would have varying effects on the melt flow during the injection process. To influence the polymer melt, grooves were formed both perpendicular and parallel to the flow direction. In injection moulding, the mould cavity is filled by a complex, expansive flow, which results in the formation of a shell-core structure that varies depending on the process parameters. This study aims to investigate the influence of microstructures formed on the mould surface on the fatigue performance of different test specimens. The microstructures generated on the mould surface can directly impact the internal material structure of the moulded product and indirectly affect the bonding strength of associated elements, such as composite layers. Understanding these effects is crucial for optimizing the mechanical properties and durability of injection-moulded components, particularly in applications requiring high-performance materials.

1.1 FATIGUE TEST EQUIPMENT

The fatigue testing machine (**Figure 2**) operates on the principle of resonance, meaning that the test specimen, along with the attached clamping part, forms an oscillating system within the testing machine. This setup allows for precise replication of cyclic loading conditions, ensuring that the frequency of the machine corresponds exactly to the natural frequency of the test specimens. The machine mechanically transfers the applied load to the test specimen, simulating real-world fatigue conditions. This method is highly effective for studying the fatigue behavior of materials under controlled and repeatable conditions, which is essential for developing accurate fatigue life predictions. The polymer fatigue testing machine at the John von Neumann University is designed by Sebők and Fodor [15]. The device is designed to accommodate standard tensile test specimens, which means that, according to the task requirements, standard workpieces will need to be produced and tested to carry out fatigue testing and measurements.

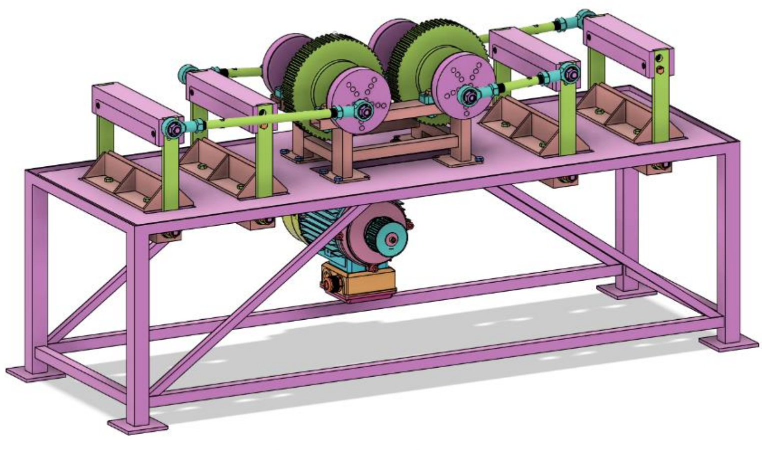

Figure 2. The fatigue testing machine.

1.2 LASER STRUCTURED INJECTION MOULDING CAVITY

The process was carried out using a Monaco 1035-80-40 industrial femtosecond laser equipped with a LINOS F-Theta-Ronar scanning optics system and a focal length lens of f = 254 mm. The power laser was calibrated based on the literature [8],[9], aiming to achieve a microstructure depth capable of influencing the polymer flow during injection moulding. Such as pulse energy and scanning speed can precisely control the depth and shape of microstructures, impacting the flow behaviour and, consequently, the mechanical properties of the final product.

Creating grooves on the mould surface that are parallel or perpendicular to the polymer melt flow could potentially have distinct effects on the final properties of the moulded product (**Figure 3**). Grooves aligned parallel to the flow direction might streamline the flow, potentially reducing turbulence and leading to a more uniform alignment of polymer chains along the flow. This alignment could enhance properties such as tensile strength and stiffness in that direction. Conversely, grooves oriented perpendicular to the flow might introduce disruptions in the polymer alignment, which could potentially increase shear forces and promote a more complex internal structure. This disruption might improve the material's resistance to crack propagation and increase its toughness.

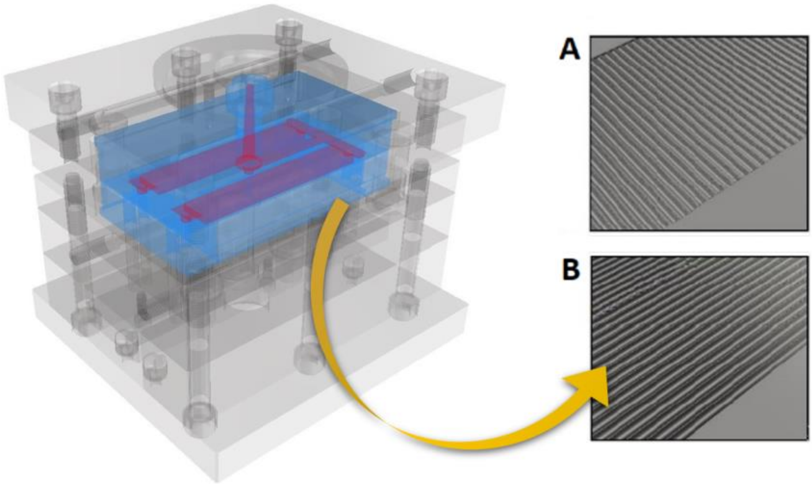

Figure 3. The injection moulding tool and its microstructured cavity: A – perpendicular, B – parallel to the flow front.

After creating micro-grooves oriented both parallel and perpendicular to the melt flow direction on the mould cavity surface (**Figure 4**), the treated area was analysed with a Keyence VHX-2000 digital microscope to verify the groove depth. The analysis revealed an average depth of 83 µm. This depth was observed both in the surface-treated parts parallel and perpendicular to the direction of flow.

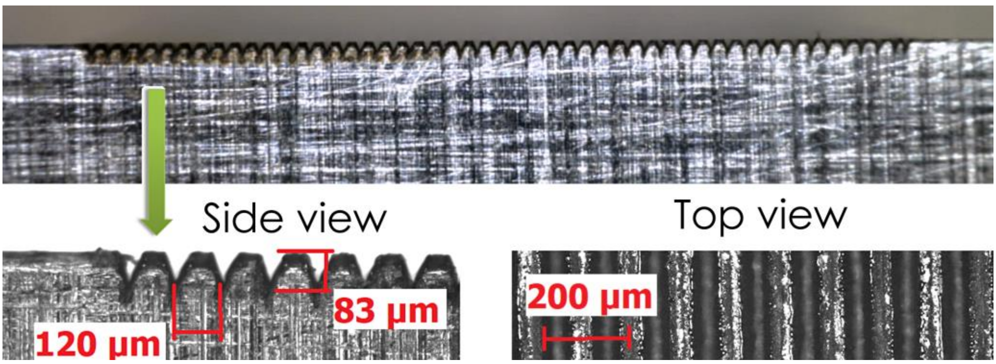

Figure 4. A microscopic image of the cavity surface with dimensions.

1.3 POLYPROPYLENE RAW MATERIAL

The selection of the base material was influenced by its suitability for technical applications and favourable manufacturing properties. Polypropylene (PP) was chosen, specifically a thermoplastic random copolymer known as Tatren RM 85 82 Clear. This material is characterized by its high flowability and excellent processing stability. According to its technical datasheet, it can be processed efficiently using conventional injection moulding machines at temperatures ranging from 190 to 230 °C. The test specimens were produced following the recommended processing parameters outlined in the datasheet [16], ensuring optimal material performance and consistency during manufacturing.

2. ANALYSIS

The applied test specimens were selected based on the results of the initial bending tests. The testing frequency was set to 5 Hz, as recommended in the literature [15]. In the first phase, the specimens were subjected to 1,000 cycles, followed by 10,000 cycles in the second phase, 100,000 cycles in the third, and 1,000,000 cycles in the final phase. The bending amplitude used during testing was 10 mm. All fatigue tests were conducted at room temperature. During the fatigue testing (**Figure 5**), the specimens were monitored using a thermal camera to observe temperature changes. The desired bending amplitude was achieved by adjusting the eccentric discs mounted on the transmission shafts, allowing precise control over the mechanical loading conditions.

To establish a reference for the effect of the structured surfaces, test specimens were also produced using an untreated mould insert with a ground surface. This allowed for direct comparison between the structured and non-structured surfaces, providing a baseline to evaluate the influence of the microstructures on the mechanical properties and behaviour of the specimens. 25 samples per type were compared.

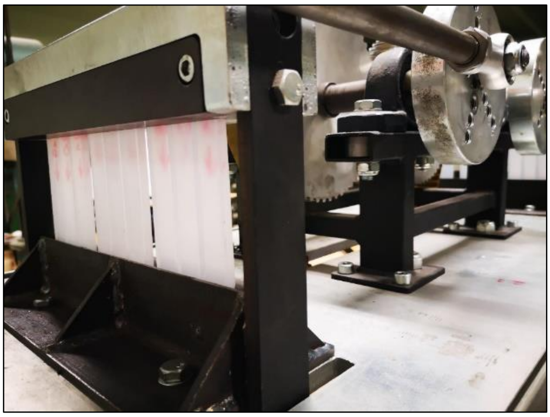

Figure 5. In-process photo of the fatigue test.

3. RESULTS AND DISCUSSION

In the earlier tests at 1,000, 10,000, and 100,000 cycles, all specimens exhibited similar flexural strength, showing no significant differences in performance (Figure 6). However, at the one million cycle test, only the specimens with parallel microstructures were able to retain their initial flexural strength values, while those with other structures showed a decline. This suggests that the alignment of polymer chains along the parallel grooves enhances load distribution and reduces stress concentrations during extended cyclic loading.

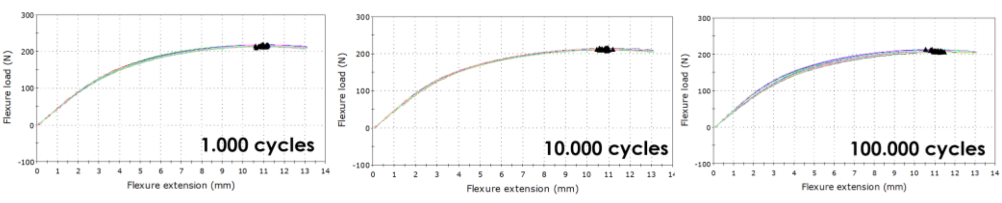

Figure 6. Flexural Strength Comparison of Specimens after 1000, 10 000, and 100 000 Cycles.

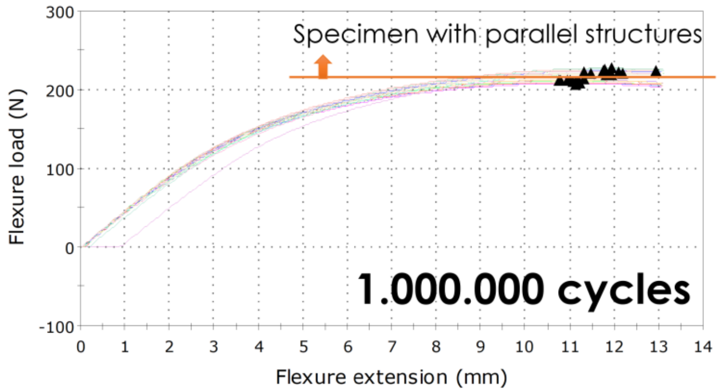

Figure 7. Flexural Strength Retention of Parallel and Perpendicular Microstructures after One Million Cycles.

The measured difference in flexural strength between the parallel structures and the perpendicular or ground surfaces ranged from 5 to 8%. This suggests that the parallel microstructures are more effective in maintaining the material's mechanical properties over extended fatigue testing (**Figure 7**). Their ability to align polymer chains along the groove direction likely contributes to better stress distribution and reduced strain concentration, which helps prevent early strength degradation compared to the other surface configurations.

AKNOWLEDGEMENT

This work was supported by the National Laboratory for Renewable Energy (Project no. RRF-2.3.1-21-2022-00009), which has been implemented with the support provided by the Recovery and Resilience Facility of the European Union within the framework of Programme Széchenyi Plan Plus, Hungary.

REFERENCES

[1] Maghrour Zefreh Mohammad, Adam Torok. Theoretical Comparison of the effects of different traffic conditions on urban road environmental external costs. Sustainability March 2021; 13:3541. https://doi.org/10.3390/su13063541

[2] Vodovozov Valery, Raud Zoja, Petlenkov Eduard. Review of energy challenges and horizons of hydrogen city buses. Energies September 2022; 15:6945. https://doi.org/10.3390/en15196945

[3] Wróbel Kamil, et al. Hydrogen internal combustion engine vehicles: a review. Energies November 2022; 15:8937. https://doi.org/10.3390/en15238937

[4] Fan Lixin, Tu Zhengkai, Chan Siew Hwa. Recent development of hydrogen and fuel cell technologies: a review. Energy Rep November 2021; 7:8421e46. https://doi.org/10.1016/j.egyr.2021.08.003

[5] Manoharan Yogesh, et al. Hydrogen fuel cell vehicles; current status and future prospect. Appl Sci June 2019; 9:2296. https://doi.org/10.3390/app9112296 [Online].

[6] Ioan-Sorin Sorlei, et al. Fuel cell electric vehicles – a brief review of current topologies and energy management strategies. Energies January 2021;14:252. https://doi.org/10.3390/en14010252

[7] Kis, Dávid István, and Eszter Kókai. "A review on the factors of liner collapse in type IV hydrogen storage vessels." *International Journal of Hydrogen Energy* (2023). https://doi.org/10.1016/j.ijhydene.2023.09.316

[8] Berczeli, M., and Z. Weltsch. "Improvement of adhesive joining of hybrid aluminum–GFRP using surface modifications." *IOP Conference Series: Materials Science and Engineering*. Vol. 448. No. 1. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/448/1/012050

[9] Weltsch, Zoltan, Ferenc Tajti, and Miklós Berczeli. "Development of the bonding technology of modern automotive materials with environmentally friendly solutions." *KOMUNIKACIE/COMMUNICATIONS* 26.2 (2024): B135-B141. https://doi.org/10.26552/com.C.2024.026

[10] Mortazavian, S., and A. Fatemi. "Tensile and fatigue behaviors of polymers for automotive applications: Zähigkeits-und Ermüdungsverhalten von Polymeren für Automobilanwendungen." *Materialwissenschaft und Werkstofftechnik* 46.2 (2015): 204-213. https://doi.org/10.1002/mawe.201400376

[11] Ahmadifar, Mohammad, et al. "Exploring fatigue characteristics of metallic boss-polymer liner adhesion in hydrogen storage tanks: Experimental insights post surface treatment." *Journal of Energy Storage* 75 (2024): 109771. https://doi.org/10.1016/j.est.2023.109771

[12] Azadi, M., et al. "High-cycle bending fatigue properties of additive-manufactured ABS and PLA polymers fabricated by fused deposition modeling 3D-printing." *Forces in Mechanics* 3 (2021): 100016. https://doi.org/10.1016/j.finmec.2021.100016

[13] Safai, Lauren, et al. "A review of the fatigue behavior of 3D printed polymers." *Additive manufacturing* 28 (2019): 87-97. https://doi.org/10.1016/j.addma.2019.03.023

[14] Guo, Rui, et al. "The fatigue performances of carbon fiber reinforced polymer composites–a review." *Journal of Materials Research and Technology* 21 (2022): 4773-4789. https://doi.org/10.1016/j.jmrt.2022.11.053

[15] Fodor, Antal, and Pál Boza. "Designing Fatigue Experiment for Investigating Polymer Specimens." *MACRo*. 2015.

[16] Material Datasheet - Polypropylene Tatren RM 85 82 Clear https://molgroupchemicals.com/userfiles/products/80/80_tds_en.pdf Seen: 2024. Sept.