CHANGE IN MECHANICAL PROPERTIES OF BALLISTIC MATERIALS AFTER EXPOSURE TO EXTREME ENVIRONMENTS

[1]Ondrej LINKA, [2]Jindrich VILIS, [2]Zbynek STUDENY

[1]*University of Defence, Faculty of Military Technology, Brno, Czech Republic, EU, ondrej.linka@unob.cz*

[2]*University of Defence, Faculty of Military Technology, Department of Mechanical Engineering, Brno, Czech Republic, EU, jindrich.vilis@unob.cz, zbynek.studeny@unob.cz*

https://doi.org/10.37904/metal.2025.5098

Abstract

The subject of this thesis is to perform mechanical tests of rigid ballistic protection made of composite materials. The topic builds on already developed composite ballistic materials and complements the study of mechanical properties by assessing the changes in these properties after exposure to ultraviolet (UV) electromagnetic radiation. The work uses existing research on the Twaron® material and previously determined strength reduction values after 1-month exposure. Experimental samples of composite plates made of this material will be produced using selected manufacturing technologies based on previous analysis. Mechanical properties of the samples will be measured after 4-month exposure in a defined environment and the results will be compared. Practical tests will be performed to determine the influence of manufacturing technology and the environment on the measured mechanical properties.

Keywords: Mechanical testing, ballistic protection, Twaron, material degradation

1. INTRODUCTION

As current requirements for ballistic protection of objects or individuals change, the defense industry often relies on materials with excellent protective properties while maintaining a favourable weight factor. This enables better mobility while maintaining the same level of protection.

However, these materials often degrade significantly faster than previously used protective elements, such as steel plates, especially when exposed to UV radiation. The most widely used representative of such materials is Kevlar. For Kevlar protective components, there is a specified service life during which the product retains its protective effect. This period is reduced depending on the environmental exposure, and polyamides, including Kevlar, are particularly sensitive to photodegradation. Armed forces around the world are creating pressure on technology companies to extend the lifespan of ballistic protection systems, which would reduce the cost of replacement and lower the logistical burden related to transportation, replacement, and disposal of worn-out parts. The lifetime of these materials can be prolonged when stored in proper conditions and protected from direct exposure to degrading factors during use [1-3].

2. MATERIALS AND MEASUREMENT METHODS

For the measurements, we used Twaron® material produced by Teijin Aramid in three forms: Twaron 747 VARTM, Twaron 747 ER68, and Twaron 747 TH110. The preparation of samples from these materials was carried out using waterjet cutting technology. [1]

For the tensile test, the samples were prepared with dimensions: L = 250 mm, h = 2.5 mm, b = 25 mm.

For the bending test, the samples were prepared with dimensions: L = 80 mm, h = 5 mm, b = 10 mm.

2.1 Twaron

Twaron is a high-strength fiber produced by Teijin Aramid. It is a para-aramid fiber with a polymer component of poly(p-phenylene terephthalamide) (PPTA). It is a linear aromatic polyamide formed through a polycondensation process. During the reaction of the initial monomers, strong amide bonds –CO–NH– are created, which allow the connection of aromatic rings into long chains. The molecular structure of Twaron is shown in **Figure 1**. Twaron is used for its excellent mechanical properties, which include high tensile strength, abrasion resistance, chemical stability under elevated temperatures, and low electrical conductivity. Due to these properties, it is used in the production of ballistic protection for both military and civilian applications. [1-5]

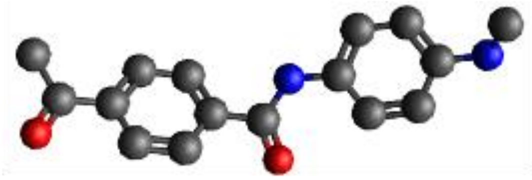

Figure 1 Twaron molecule

2.2 Twaron 747 composite variants

The Twaron 747 reinforcement was processed in three variants, differing in the type of resin used and the manufacturing technology applied.

The **VARTM** variant was impregnated with LG700 epoxy resin and HG700 hardener using the Vacuum Assisted Resin Transfer Molding method. The process was carried out at room temperature (22 °C) for 24 hours, resulting in uniform resin distribution and improved fabric properties [2].

The **ER68** variant utilized thermoset epoxy resin ER68 and was processed in an autoclave at temperatures ranging from 130 to 200 °C and pressures from 3 to 10 bar, depending on the material-resin combination. Enhanced mechanical performance was achieved through subsequent hot-pressing at 120 °C with a force of 350 kN for 60 minutes [2].

In the **TH110** variant, a thermoplastic resin in foil form was inserted between fabric layers and bonded into the Twaron structure via hot-pressing at 140 °C and 350 kN [2].

All processing approaches aimed to optimize the final mechanical performance of the composite material.

2.3 Experimental methods of mechanical properties testing

To measure the mechanical properties of the selected materials, two types of tests were used – tensile test and bending test. These methods were chosen because of the amount of information they provide, as tensile and flexural strength values are key for the preliminary assessment of the ballistic resistance of a material and its ability to withstand damage caused by bullet impact. To obtain reference values, tests were first carried out on material that had not been exposed to UV radiation at all, followed by tests on material exposed to UV radiation for 1 month, and finally on material irradiated for 4 months.

The tensile tests were carried out in the laboratory of the Department of Mechanical Engineering at the University of Defense using a calibrated ZWICK Z100 machine. The measurements conformed to ČSN EN ISO 527-1 and the samples were clamped using grips. The aim of the testing was to determine the tensile and yield strength of each material after different durations of UV exposure, in order to assess how the mechanical properties changed due to the photo-oxidation effect in the material [6] (see **Figure 2**).

The bending tests were also conducted in the laboratory of the Department of Mechanical Engineering at the University of Defense using a calibrated ZWICK Z100 machine. The tests were carried out under the conditions specified by ČSN EN ISO 178, where the supports consisted of two steel blocks spaced 64 mm apart, and the load was applied using a bending mandrel with a tip diameter of 8 mm. The bending test provides information about how the material resists plastic deformation under load [7] (see **Figure 3**).

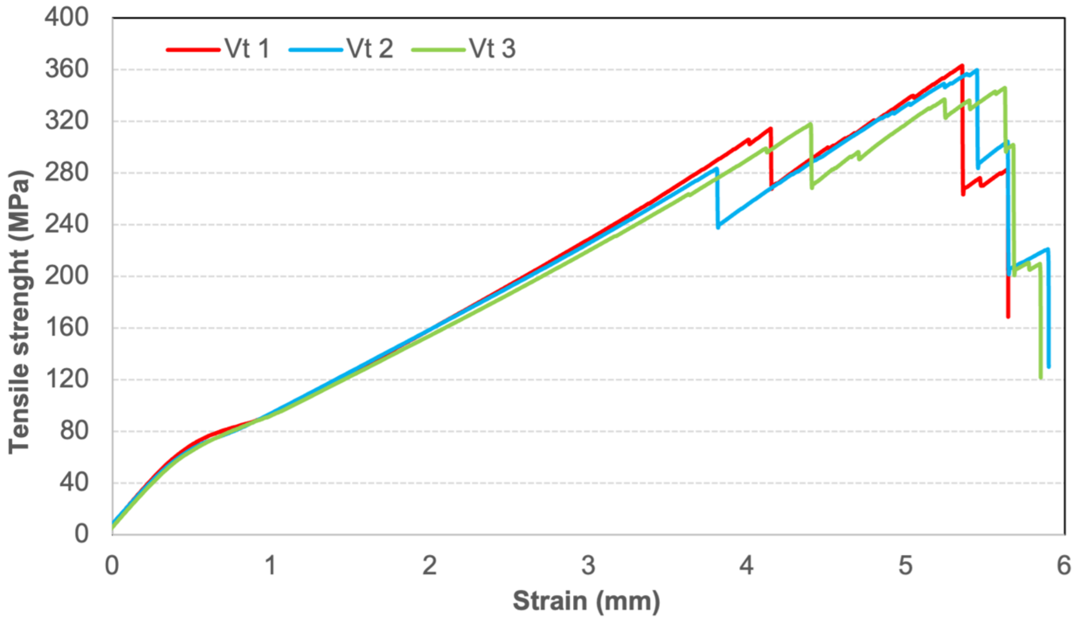

Figure 2 Tensile test curve of Twaron 747 VARTM after 4-month exposure

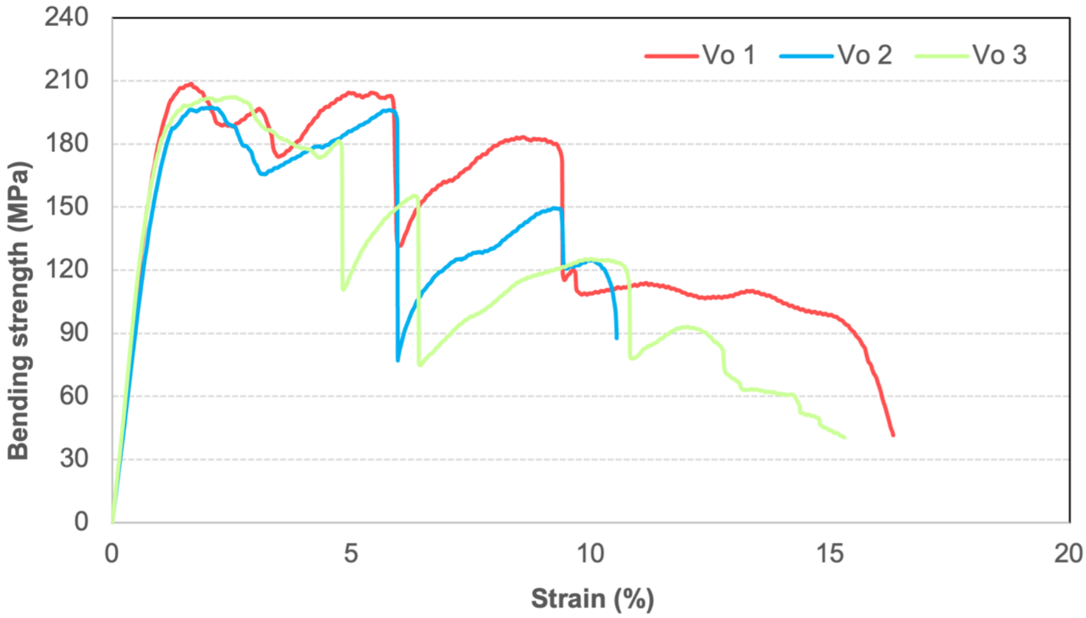

Figure 3 Bending test curve of Twaron 747 VARTM after 4-month exposure

2.4 Photo-oxidation process of material degradation

After exposure to electromagnetic radiation in the UV region, a large part of polymer materials are affected to the point that their mechanical (strength, ductility, corrosion resistance) and physical (reflectance) properties are changed. Changes in these properties in polymer materials are caused by a effect called photo-oxidation. This is a process in which the absorption of photons of specific wavelengths and the subsequent excitation of electrons to higher quantum states results in the breakdown of chemical bonds in macromolecules. The result is the breaking of the polymer chain often associated with the formation of free radicals that trigger secondary chemical reactions. [8,9]

2.5 Simulation of long-term UV exposure

In order to obtain the values of the material exposed to long-term solar radiation, it was necessary to simulate the exposure conditions in the laboratory in a test chamber device capable of so-called artificial ageing by using UV radiation. Due to the higher UV intensity generated by the Q-SUN Xenon Test Chambre Model Xe-3, which uses a quartz glass xenon lamp, it is possible to simulate this artificial ageing. The chamber can irradiate objects using UV radiation with wavelengths in the range of 290-400 nm, whereby polyamides are most sensitive to wavelengths in the range of 250-310 nm. The UV exposure process was in accordance with ISO 4892-2 and the materials were exposed to UV radiation in the chamber for 1 and 4 months [10].

3. MEASUREMENT RESULTS

The tensile strength test results are shown in **Figure 4** and the bending strength test results are shown in **Figure 5**. The values are supplemented with standard deviations, which indicate the variation in the measured results.

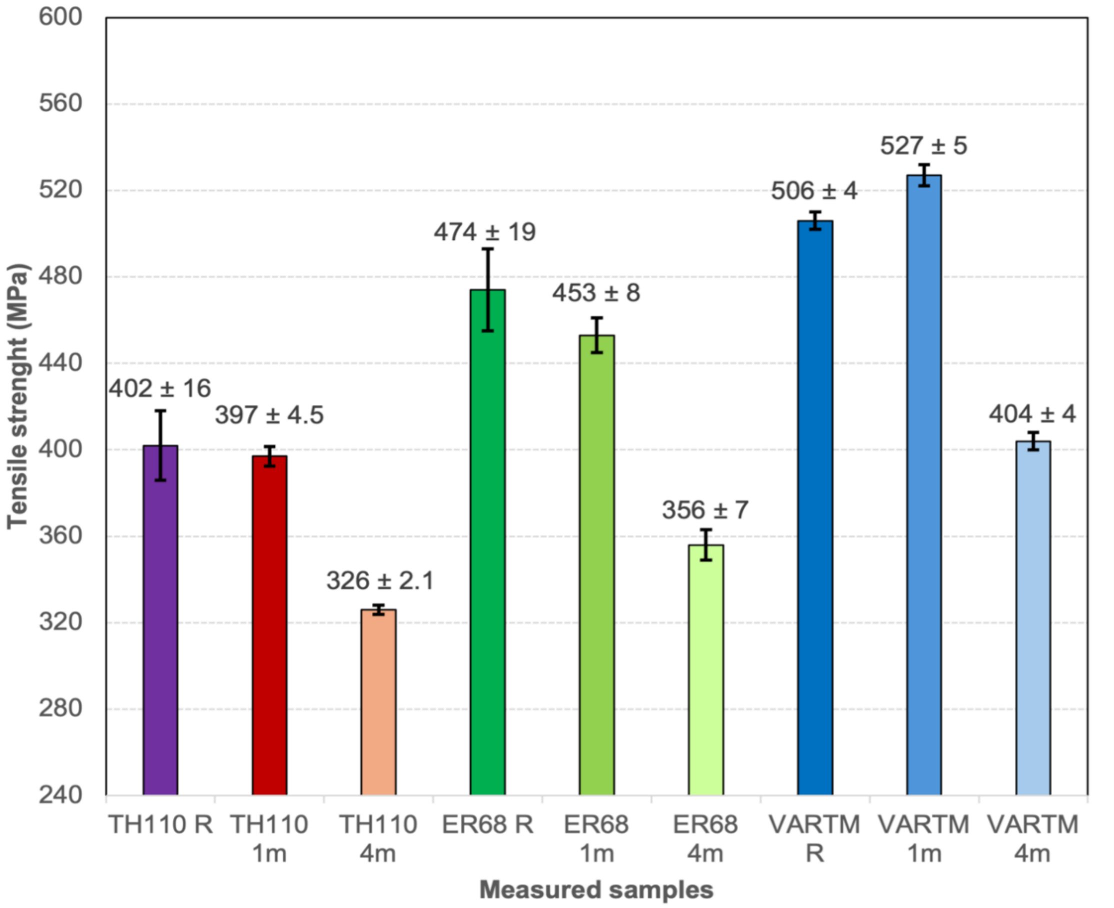

Figure 4 Graph of tensile strength values

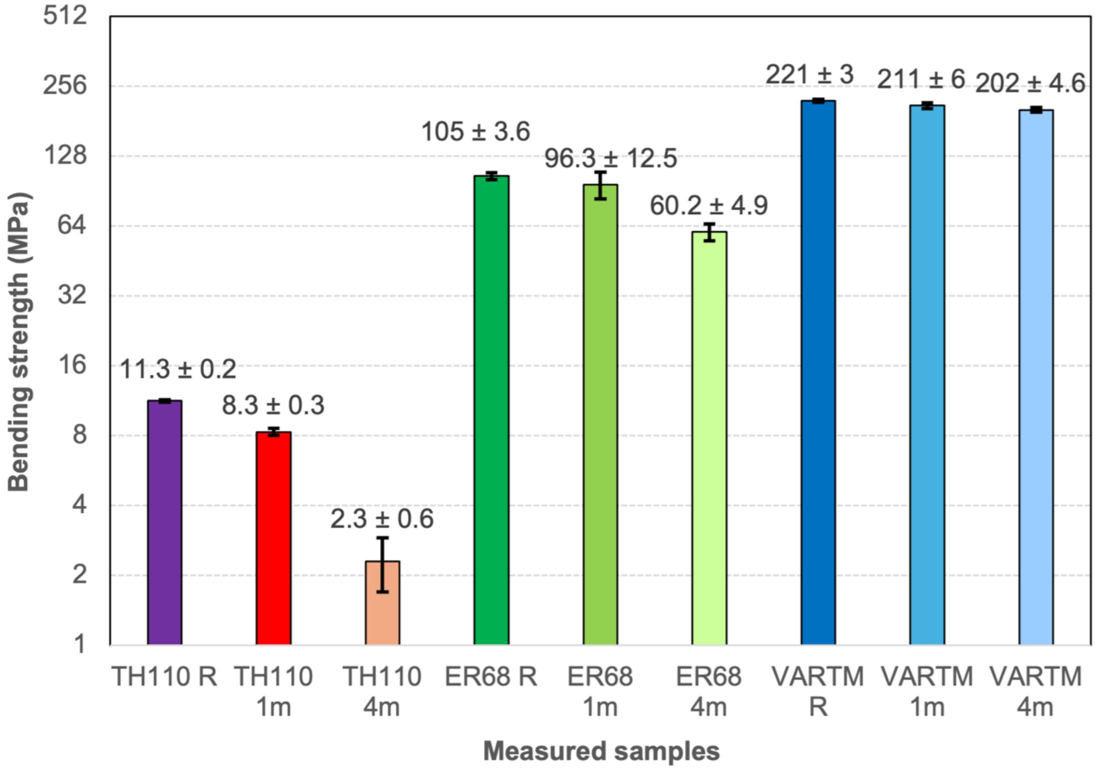

Figure 5 Graph of bending strength values

4. DISCUSSION OF RESULTS

The most significant decrease in mechanical properties due to UV radiation was observed in the Twaron 747 TH110 material. The bending strength dropped by almost 80 % compared to the reference values, which can be considered as an almost complete loss of the material's ability to resist this type of mechanical stress. The cause can clearly be attributed to the photo-oxidation phenomenon, which disrupted the macromolecular bonds within the fabric structure, significantly weakening the material's cohesion. This result is in line with the expected theoretical behaviour of polymer composites exposed to UV radiation. A significant decrease of approximately 19 % in tensile strength was also recorded for this material.

The difference in the extent of degradation between flexural and tensile loading can be explained by the fact that the degradation of the resin matrix manifests more strongly under flexural stress than under tensile stress.

On the other hand, Twaron 747 VARTM exhibited the highest resistance to UV radiation, with an approximate 9 % decrease in bending strength and around 20 % in tensile strength. An interesting observation is the slight increase in tensile strength after one month of exposure – approximately 4 % – indicating a different degradation mechanism. The most likely explanation is partial embrittlement of the resin in the surface layer, which may lead to increased stiffness and, consequently, a temporary rise in tensile strength. This assumption is supported by the results of the bending tests, where a slight strength loss of around 5 % was recorded over the same period. However, after prolonged exposure (4 months), even this material showed a decrease in strength, confirming that the long-term effect of UV radiation causes progressive degradation in the deeper layers of the composite, negating the initial compensatory effect of the embrittled resin.

5. CONCLUSION

Based on the conducted experiment, it can be concluded that long-term exposure to UV radiation has a demonstrably negative impact on the mechanical properties of polymer composites. With increasing exposure time, progressive degradation of the material occurs, manifested by a significant decrease in tensile and flexural strength. These findings confirm that UV radiation is a major degradation factor that must be considered in the design of polymer fabric products, especially when they are intended for severe deployment conditions. The results also underline the need for a detailed experimental verification of the long-term stability of the material against environmental influences, not only in terms of UV radiation but also other influences (e.g. humidity, temperature). It is also necessary to ensure optimum storage conditions to prolong the functional life of the materials.

For further research, it may be recommended to extend the experiment with a larger number of samples and longer exposure times, as well as to verify the effectiveness of different types of protective layers in terms of maintaining the mechanical properties of the composite during long-term ageing.

ACKNOWLEDGEMENTS

This research was funded by the specific research project "SV23-216" at the Department of Mechanical Engineering, University of Defence in Brno, as well as by the "VAROPS (DZRO VAROPS) Military autonomous and robotic assets" development project supported by the Ministry of Defence of the Czech Republic.

REFERENCES

[1] NASCIMENTO, R. F., SILVA, A. O. DA, WEBER, R. P., MONTEIRO, S. N. Influence of UV radiation and moisten associated with natural weathering on the ballistic performance of aramid fabric armor. *Journal of Materials Research and Technology*. 2020, vol. 9, no. 5, pp. 10334–10345. DOI: 10.1016/j.jmrt.2020.07.046.

[2] VILIŠ, J., KUSMIČ, D., PHAN, B. T., ZOUHAR, J., POKORNÝ, Z., ŠAFL, P., LINKA, O. Influence of Water Absorption on Tensile and Flexural Properties of Composite Samples. In: *33rd International Conference on Metallurgy and Materials, METAL 2024*. Ostrava: TANGER Ltd., 2024, pp. 461–466. ISBN: 978-80-88365-21-1. DOI: 10.37904/metal.2024.4908.

[3] CEOROMILA, A. C., DELEANU, L., POPESCU, C., LOM, I., VASILIU, A. V., SEICIU, P. L., OJOC, G. G., SANDU, S. M. SEM Investigation of Failure Mechanisms in Twaron® Aramid Fibers Used for Personal Armors. *Polymers*. 2025, vol. 17, no. 8. DOI: 10.3390/polym17081058.

[4] XU, Y. J., ZHANG, H., HUANG, G. Y. Ballistic Performance of B_4C/STF/Twaron Composite Fabric. *Composite Structures*. 2022, vol. 279. DOI: 10.1016/j.compstruct.2021.114754.

[5] NAVEEN, J., JAYAKRISHNA, K., HAMEED SULTAN, M. T. B., AMIR, S. M. M. Ballistic Performance of Natural Fiber Based Soft and Hard Body Armour – A Mini Review. *Frontiers in Materials*. 2020, vol. 7. DOI: 10.3389/fmats.2020.608139.

[6] EN ISO 527-1:2020. Plastics-Determination of Tensile Properties-part 1: General Principles. ISO (International Organization for Standardization), Geneva, Switzerland, 2020.

[7] EN ISO 178:2019. *Plastics — Determination of flexural properties*. ISO (International Organization for Standardization), Geneva, Switzerland, 2019.

[8] XU, Y., ZHANG, H., HUANG, G. Review on the Mechanical Deterioration Mechanism of Aramid Fabric under Harsh Environmental Conditions. *Polymer Testing*. 2023, vol. 128. DOI: 10.1016/j.polymertesting.2023.108227.

[9] HOQUE, M. S., DOLEZ, P. I. Aging of High-Performance Fibers Used in Firefighters' Protective Clothing: State of the Knowledge and Path Forward. *Journal of Applied Polymer Science*. 2023, vol. 140, no. 32. DOI: 10.1002/app.54255.

[10] ISO 4892-2:2013. Plastics – Methods of exposure to laboratory light sources – Part 2: Xenon-arc lamps. Geneva: International Organization for Standardization, 2013.