

UV-induced surface oxidation of PEEK: Correlation between resin penetration dynamics and dielectric breakdown strength

Akos Levente Kokai^{a,b,*}, Peter Baumli^a, Zoltán Erdélyi^c, Tamas Fodor^e, George Kaptay^{a,d}

^a Institute of Metallurgy, Metal Forming and Nanotechnology, University of Miskolc, Egyetem út 1, H-3515, Miskolc, Hungary

^b Audi Hungaria Zrt. H-9027 Győr, Hungary

^c Faculty of Science and Technology, Institute of Physics, Department of Solid-State Physics, University of Debrecen, H-4026, Debrecen, Hungary

^d HUN-REN-ME Materials Science Research Group, University of Miskolc, Egyetem út 1, H-3515, Miskolc, Hungary

^e HUN-REN Institute for Nuclear Research, H-4002, Debrecen, Hungary

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ABSTRACT

This study investigates how UV-induced surface oxidation of PEEK coatings influences the capillary-driven penetration of liquid, uncured epoxy resin in rectangular capillaries formed by PEEK-coated hairpin wires, as well as the dielectric breakdown strength measured under a modified test configuration. UV irradiation was applied at various intensities and exposure times, and the resulting changes in surface chemistry were characterized by FTIR, Raman spectroscopy and XPS, while AFM was used to visualize nanoscale topographical variations. Resin penetration behavior was evaluated at 40, 60 and 80 °C. Dielectric breakdown strength was assessed using a setup based on the voltage-ramp prescriptions of IEC 60851-5 but employing a modified ground-electrode configuration (water medium) rather than full standard compliance. UV irradiation induced the formation of carbonyl and carboxyl/carboxylate groups, which correlated with a reduction in resin penetration time of up to ~30%. Nanoscale surface features disappeared after UV exposure, although roughness parameters did not show a consistent trend due to substrate waviness. Breakdown strength decreased already at the lowest UV irradiation specific energy indicating a threshold-like behavior with no significant changes at higher exposures. As the tests were performed in tap water, the measured dielectric values may reflect the combined influence of surface oxidation and the ionic test environment. Overall, UV-induced oxidation enhances resin penetration but is associated with a reduction in dielectric breakdown strength under the present test conditions, highlighting a non-linear trade-off between impregnation efficiency and electrical robustness.

1. Introduction

Polyether ether ketone (PEEK) is a high-performance, semi-crystalline thermoplastic known for its excellent mechanical strength and thermal stability [1]. These properties make it suitable for demanding applications in the automotive, aerospace, and medical industries [2]. In the automotive sector, PEEK is increasingly applied as a thin insulating coating on rectangular copper conductors used in hairpin windings, where components must withstand elevated electrical and thermal loads driven by the growing electrification demands [3,4]. Windings of electric motors are usually made of copper or aluminum wires, coated with an insulating polymer [5]. To ensure proper insulation in such

environments, trickle impregnation with polymer resins is commonly employed during electric motor manufacturing [6–8]. During the trickle impregnation process, the windings of electric motors are impregnated with a liquid, uncured epoxy or polyester resin [7,9]. Interfacial phenomena play a crucial role in how the resin penetrates the narrow rectangular capillaries within the windings [10]. After the penetration phase is completed, the resin is cured, forming a continuous insulation layer throughout the motor [11]. In this study, controlled UV irradiation was applied to the outer PEEK coating of simplified, hairpin-like laboratory samples in order to investigate the fundamental effect of surface oxidation on resin penetration behavior and dielectric performance.

Due to its chemical structure, comprising aromatic rings and ketone

* Corresponding author.

E-mail addresses: kokai.akos.levente@student.uni-miskolc.hu (A.L. Kokai), peter.baumli@uni-miskolc.hu (P. Baumli), zoltan.erdelyi@science.unideb.hu (Z. Erdélyi), fodor.tamas@atomki.hu (T. Fodor), kaptay@hotmail.com (G. Kaptay).

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groups, PEEK is inherently hydrophobic and chemically inert, exhibiting low surface energy. This significantly limits its interaction with polar liquids, such as impregnating resins, and results in poor adhesion [2, 12–14]. To overcome this, several surface modification techniques have been developed to enhance the surface wettability and adhesion properties of polymers [13,15], including surface grafting [16], corona discharge [17], plasma treatment [18], laser ablation [19] and ultraviolet (UV) irradiation [20]. These treatments introduce polar functional groups onto the polymer surface, which increase surface energy and improve resin wetting and bonding [21–23]. Among these modifications, UV irradiation is particularly relevant for PEEK because it can generate reactive oxygen species that break aromatic and ether linkages, leading to the formation of carbonyl, carboxylic and carboxylate groups—chemical transformations that substantially alter surface polarity without necessarily increasing surface roughness.

Among these, UV irradiation offers a simple and scalable method for surface modification and is widely applied across industries. Giancaterina et al. [24] studied the photochemical response of PEEK under polychromatic UV irradiation and observed significant structural degradation with the formation of low molecular weight products such as carbon dioxide, carbonyl groups, and carboxylic acids. Their results showed that UV exposure leads to ether-bond cleavage, chain scission, and aromatic ring-opening reactions, producing hydroxyl-, carbonyl- and carboxyl-containing species—confirming that UV triggers both direct photolysis and oxidative transformation mechanisms. During such UV-induced oxidation, the surface oxygen content increases, typically reaching a saturation level around 30 atomic percent after 4–5 min of exposure. As a result, water contact angles tend to decrease, suggesting improved surface polarity and wettability [25–27].

Plasma treatment, while effective, often increases surface roughness, which may hinder certain applications [28]. In contrast, methods involving active oxygen species (AOS) generated by UV irradiation have been shown to enhance surface functionality while preserving smoothness [29–30]. For instance, Yoshida et al. [31] demonstrated that UV-AOS treatment significantly improves the adhesion of copper coatings to PEEK surfaces, achieving an adhesion energy of up to 0.15 J/m^2 . Unlike plasma-treated surfaces, the AOS-modified surfaces remained smoother, which is beneficial in applications like printed circuit boards where low roughness is critical.

PEEK also exhibits outstanding dielectric properties, making it a suitable material for electrical insulation. Giants et al. [32] found that reduced crystallinity lowers dielectric breakdown strength, while Ho et al. [33] reported the same at elevated temperatures.

However, surface modifications that improve wettability may also influence dielectric properties. For example, Asada et al. [34] observed that carbonyl groups on oxidized low-density polyethylene (LDPE) act as trap sites at low concentration—reducing leakage current—but transform into hopping sites at higher concentrations, ultimately reducing dielectric strength [34–35]. Tong et al. [36] found that polyamides containing carbonyl functionalities exhibit enhanced dielectric properties due to improved chain packing and increased dipole density. These examples illustrate that the introduction of polar oxygen-containing groups can either improve or impair dielectric behavior, depending on their concentration and the underlying polymer structure—a consideration that is also relevant when evaluating UV-induced oxidation effects on PEEK.

The penetration of impregnating resins into the rectangular capillaries formed by PEEK-coated copper hairpins in electric motors is governed by interfacial capillary force, which in turn depends strongly on the contact angle of the resin on the substrate surface [37–50]. Therefore, any surface treatment—including UV irradiation—can affect both adhesion energy of the resin to PEEK and the dynamics of resin impregnation.

Despite the extensive research on UV-induced degradation of PEEK, the consequences of surface oxidation on the functional performance of PEEK-coated conductors under impregnation-relevant conditions

remain unclear. In particular, the combined influence of oxidation-derived surface chemistry on resin impregnation kinetics and dielectric breakdown strength has not been systematically investigated in previous studies on PEEK-coated conductors.

This study addresses this knowledge gap by investigating the correlation between UV irradiation specific intensity and duration, surface oxidation state, and epoxy resin penetration behavior in rectangular capillaries formed by PEEK-coated copper hairpins. Additionally, the effect of these surface modifications on the dielectric breakdown strength is assessed on the same oxidation states. By combining spectroscopic, morphological, and functional measurements, this work aims to provide a quantitative correlation between surface oxygen concentration (XPS at%) and functional properties, offering insights into the fundamental interfacial mechanisms governing capillary-driven resin penetration and surface-controlled dielectric behavior in oxidized PEEK systems. Importantly, the experiments are conducted on simplified hairpin-like laboratory samples, allowing the isolated study of surface effects under controlled laboratory conditions, without implying direct stator-level or device-scale validation.

2. Materials and methods

2.1. Materials and sample preparation

Elantas® EP 201 epoxy-based resin (abbreviated as “EP-201”) was selected as the impregnating liquid for the experiments. This resin is widely used in various automotive applications and exhibits Newtonian flow behavior. Rectangular copper hairpins commonly used in electric motor stators were employed as substrates. The sample preparation and UV irradiation setup are illustrated in Fig. 1. The bare copper conductor had nominal dimensions of $1.65 \text{ mm} \times 3.40 \text{ mm}$ and was coated with a $0.15 \pm 0.02 \text{ mm}$ thick PEEK insulation layer (see Fig. 1a). In this study, these hairpins were used as straight laboratory samples to isolate resin-PEEK interaction effects.

UV irradiation was performed using a LOCTITE UVALOC 1000 mercury lamp UV cabin, operating at a characteristic wavelength of 365 nm with four possible specific intensities: 35, 50, 70 and 110 mW/cm^2 (Henkel Corporation, Rocky Hill, CT, USA).

For the penetration experiments, 100 mm long straight PEEK-coated hairpins were cut (see Fig. 1b) and irradiated at 110 mW/cm^2 UV irradiation specific intensity during 10, 20, 30, 60, 120, 180, 240, and 300 seconds. An unirradiated reference sample was included as a reference against which the influence of UV irradiation on penetration time could be evaluated. Three sets of samples were prepared for each temperature (six sample prepared for each specific UV irradiation specific intensity and irradiation specific energy). The corresponding UV specific energies were as follows: 0, 1.1, 2.2, 3.3, 6.6, 13.2, 19.8, 26.4, and 33 J/cm^2 .

For the dielectric breakdown strength tests, straight copper conductors with a length of 500 mm were prepared using a GROB hairpin bending machine (GROB-WERKE GmbH & Co. KG, Mindelheim, Germany). The wires were bent into a U-shape with a radius of 25 mm (see Fig. 1c). The sample preparation has been conducted in accordance with the IEC 60851–5:2008 + AMD1:2011 + AMD2:2019 [51] standard. The entire outer surface of the U-shaped specimen was exposed to UV irradiation (see Fig. 1e), including both straight legs and the external arc of the bend. The inner radius of the U-bend was not irradiated due to geometric shadowing inside the UV cabin. For this investigation, five samples were prepared for each specific UV irradiation specific intensity and energy. Approximately 10 mm of insulation was removed from one end to ensure proper electrical contact. These samples were then UV-irradiated using the same durations as the penetration test series and additionally, further UV treated samples were made at lower intensities with adjusted exposure times:

- 70 mW/cm^2 : 94, 189, and 283 s (corresponding to 6.6, 13.2, and 19.8 J/cm^2)

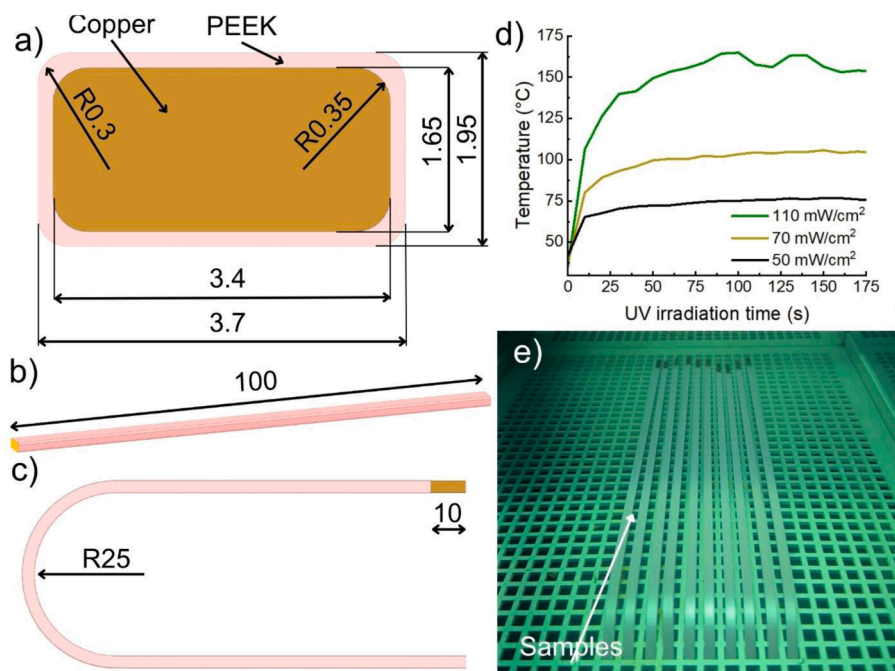


Fig. 1. Sample preparation and UV-irradiation setup: a) Cross-section and dimensions of the PEEK-coated hairpin copper conductor b) 100 mm straight pins for penetration experiments c) 500 mm U-bend pins for breakdown voltage tests d) time dependence of average sample temperatures during UV irradiation e) irradiation in the UV-cabin.

- 50 mW/cm²: 132, 264, and 396 s (corresponding to 6.6, 13.2, and 19.8 J/cm²)

During UV irradiation at 110 mW/cm², the surface temperature increased as shown in Fig. 1d, reaching a maximum value of approximately 170 °C. At lower intensities (70 and 50 mW/cm²), the maximum recorded temperatures were substantially lower. Considering that PEEK belongs to thermal class R (≥ 220 °C according to IEC 60085 [52]), the measured temperatures remain well below the threshold typically associated with bulk thermal degradation. Therefore, the observed surface modifications are primarily attributed to photochemical oxidation, although a contribution of localized surface heating to oxidation kinetics cannot be entirely excluded.

2.2. Characterization of surface chemistry and topology

After sample preparation, both quantitative and qualitative analyses of degraded surface were conducted. Fourier Transform Infrared Spectroscopy (FTIR) was performed using a Bruker Tensor 27 spectrometer equipped with a GladiATR attenuated total reflectance (ATR) reflection accessory over a measurement range of 4000–400 cm⁻¹. Raman spectroscopy was carried out using a Rigaku Xantus –1 (Rigaku Corporation, Tokyo, Japan) equipped with a diode laser excitation source operating at 532 nm. Spectra were collected on the 400–2500 cm⁻¹ wavenumber range using a 50x objective lens, a spectral resolution of 3 cm⁻¹. All measurements were conducted under ambient atmospheric conditions at room temperature (23 ± 2 °C).

X-ray photoelectron spectroscopy (XPS) was performed using a SPECS XR 50 dual-anode, non-monochromatized X-ray source in combination with a Phoibos 100 MCD-5 hemispherical energy analyzer (SPECS, Berlin, Germany). Samples were mounted on copper holders using double-sided adhesive tape and degassed overnight in a high-vacuum load-lock chamber ($\sim 10^{-7}$ mbar) before being transferred to the analysis chamber. The base pressure in the instrument was 5×10^{-10} mbar and stayed below 10^{-8} mbar during measurements. Spectra were recorded with Al K α radiation (1486.6 eV) at 10 kV acceleration voltage and 10 mA emission current (100 W X-ray power). The binding energy

scale was calibrated using the Au 4f and Cu 2p peaks of an unirradiated reference sample containing both metals, as prescribed by the manufacturer. Spectral data were processed using the CasaXPS software, the binding energy scale was fixed to the unsubstituted aromatic carbons found in PEEK (284.5 eV).

Atomic force microscopy (AFM) was conducted using a Nanosurf Flex system in dynamic (tapping) mode, equipped with a TAP190Al-G cantilever (Nanosurf AG, Liestal, Switzerland). Image resolution was 5 nm. The samples were mechanically fixed to a metal stage, and 3×3 μ m scans were recorded along the central axis at intervals of 1–2 mm. All measurements were performed under ambient conditions. Image analysis was conducted using the Gwyddion software, as recommended by the instrument manufacturer.

2.3. Penetration time measurements

Penetration time measurements (detailed discussion see in [53]) were conducted with PEEK-coated hairpin wires treated at different UV irradiation specific energies (see chapter 2.1) at three temperatures: 40 °C, 60 °C, and 80 °C, with a temperature tolerance of ± 2.5 °C. The gap between the PEEK-coated hairpin wires was set to 0.2 mm, and the capillary length was 60 mm. The liquid resin penetrated this capillary, and the penetration time was recorded based on a length scale derived from Washburn's law. The scale marks along the 60 mm capillary were located at: 0, 19.0, 26.8, 30.0, 32.9, 37.9, 42.4, 46.5, 50.2, 53.7, 56.9, and 60 mm. Then, the penetration times were recorded at these positions. The environmental conditions were maintained at 23 ± 2 °C and $30\% \pm 5\%$ relative humidity under standard atmospheric pressure. In each experiment, the applied hair pins that form the space for penetration were treated equally. High-temperatures were applied by using a Heidolph MR Hei-standard heating unit to maintain set temperatures. After each test, the hairpins were replaced, and the apparatus was cleaned with Elantas Epoxylite® EIP 4693 resin solvent. Three consecutive tests were performed under identical conditions for each case and the results were averaged.

2.4. Dielectric breakdown strength

Dielectric breakdown strength (DBS) measurements were carried out using a Schleich GLP2 device (Schleich GmbH, Hemer, Germany). The voltage was ramped at 500 V/s, with a current limit of 30 mA. The maximum applied voltage during testing was 30 kV, and the voltage ramp rate (500 V/s) was selected in accordance with the ramp conditions specified in IEC 60,851–5 (Test 13), while the overall measurement configuration did not fully comply with the standard. The measurement setup is depicted in Fig. 2. The sample geometry and mechanical preparation were based on the prescriptions of IEC 60851–5 (Test 13, Section 4.7 for rectangular wires), while the measurement setup deviated from the standard, as the IEC 60851-5 specifies the use of ≤ 2 mm steel shavings as the ground electrode. In this study, tap water was used instead of steel shot to obtain a more uniform electric field and to prevent mechanical and corona-related damage to the insulation [54–56]. However, it can be acknowledged that the use of tap water introduces ionic species that may interact with UV-modified surfaces, meaning that the measured breakdown strength may reflect a combined effect of surface oxidation and the test environment rather than the intrinsic dielectric behavior alone. (see Fig. 2) For each irradiation condition, five repeated measurements were conducted and then averaged. After each experiment, the resulting electrical breakdown voltage was divided by the layer thickness of 0.15 mm of the PEEK insulation coating to obtain electrical breakdown strength.

3. Results

3.1. Surface chemical structure changes due to UV irradiation

The absorbance spectra recorded during FTIR and Raman spectroscopy are presented in Fig. 3. The characteristic peaks of PEEK have been identified in the figure. The assigned Raman and FTIR peaks are summarized in Tables 1 and 2, respectively.

Raman spectroscopy revealed a significant decrease in the intensity of all major peaks, indicating substantial chemical changes on the PEEK surface due to UV-induced degradation and oxidation. The decline at ~ 1595 cm^{-1} suggests ring opening and formation of new functional

groups (e.g., carbonyl, carboxyl) via C=C bond disruption. Changes at 1146 cm^{-1} indicate scission of C–O–C linkages in the polymer backbone, implying chain breakage and reduced molecular weight, which may impair thermal and mechanical stability. The ~ 825 cm^{-1} C–H deformation reflects aromatic ring modification or oxidation, while the ~ 646 cm^{-1} band suggests ring distortion. No significant variation was observed near ~ 1650 cm^{-1} , associated with carbonyl groups.

In the FTIR spectra, a significant increase in intensity was observed at ~ 1216 cm^{-1} , appears to differ from some literature reports. As FTIR cannot distinguish between C–O bonds in C–O–C linkages and those in carboxylic/carboxylate groups, this increase is likely due to overlapping signals. Changes in the carbonyl (C=O) region suggest oxidative processes leading to the formation of polar functional groups along the polymer backbone (e.g., carboxylic acids, aldehydes, anhydrides). No other major spectral changes were detected.

3.2. Surface oxidation – XPS results

The recorded XPS spectra are shown in Fig. 4a)-b) and summarized in Supplementary tables S1-S2 and in Fig. 5–6. In Fig. 4a)-b), the recorded spectra are resolved into background and sub-spectra corresponding to different bonds.

The significant decrease in the C–C/C–H ratio indicates degradation of the aromatic structure, such as ring opening and fragmentation. The slight change in the C–O ratio likely reflects partial decomposition of the original ether linkages (C–O–C) in PEEK. At the same time, new C–O bonds (e.g., alcohol, carboxylic) may form, which compensates for the overall intensity, preventing a noticeable drop. The appearance of carboxylic acid/carboxylate groups (O–C=O) indicates the formation of surface-bound carboxyl functionalities –COOH (carboxylic acid) or –COO[−] (carboxylate, e.g., as salts or in dissociated form). At a specific UV dose of 33 J/cm^2 applied at 110 mW/cm^2 , the surface oxygen concentration reached approximately 30 at%, suggesting the onset of an oxidation saturation regime under these irradiation conditions reported in [25–27]. Further UV exposure at the same UV irradiation specific intensity is therefore not expected to significantly increase the measurable surface oxygen content within the detection limits of XPS.

As follows from Supplementary table S2 and Fig. 6, notable differences were observed in the XPS spectra. The $\sim 28\%$ decrease in the atomic percentage of C–C/C–H bonds suggests an inverse relationship between UV irradiation specific intensity and the integrity of the aromatic structure, indicating chain scission and ring opening in PEEK. In contrast, the formation of polar functional groups—such as carbonyl and carboxyl—is positively correlated with UV irradiation specific intensity, reflecting progressive surface oxidation. From this, it can be concluded that the more intensive the UV irradiation is, the more severe the surface oxidation is (no surface oxidation is observed at very low irradiation specific energy and at very low specific intensity).

A simplified schematic of UV-induced photodegradation and oxidation pathways in PEEK is shown in Supplementary Fig. S1, illustrating the formation of oxygen-containing functional groups detected by FTIR, Raman, and XPS.

3.3. Surface structure – AFM observations

The changes in surface structure are depicted in Fig. 7. Both micro- and nanoscale surface roughness were observed on the untreated samples. At the submicron level the roughness disappeared upon UV exposure. This suggests a slight smoothing of the surface topography as a result of the irradiation. However, this effect could not be quantitatively confirmed by surface roughness measurements. Due to the waviness of the surface introduced during manufacturing (e.g., by tool intrusion), the disappearance of these nanochannels could not be reliably detected. The surface roughness parameters showed high variability depending on the scan location, and applying aggressive filtering would distort the true topography. As a result, the AFM analysis did not yield a consistent

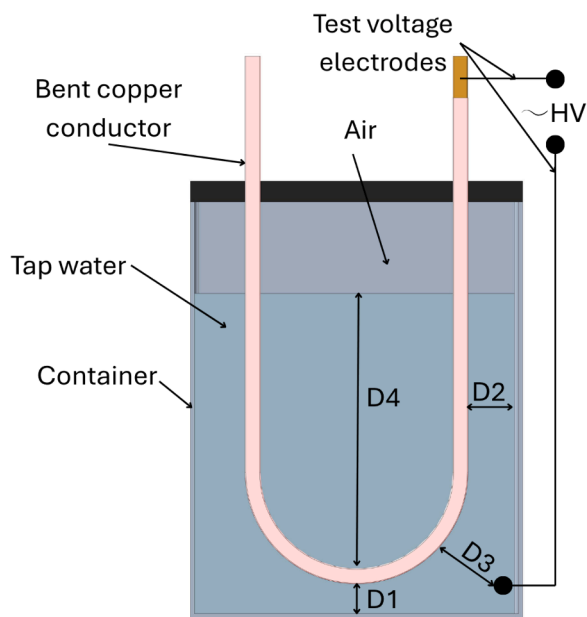


Fig. 2. Schematic drawing of the equipment based on the IEC 60851-5 geometry, used here to illustrate the dielectric breakdown test arrangement. D1 and D2 are equal to or greater than 5 mm, D3 is 30 mm, and D4 is equal to or greater than 90 mm.

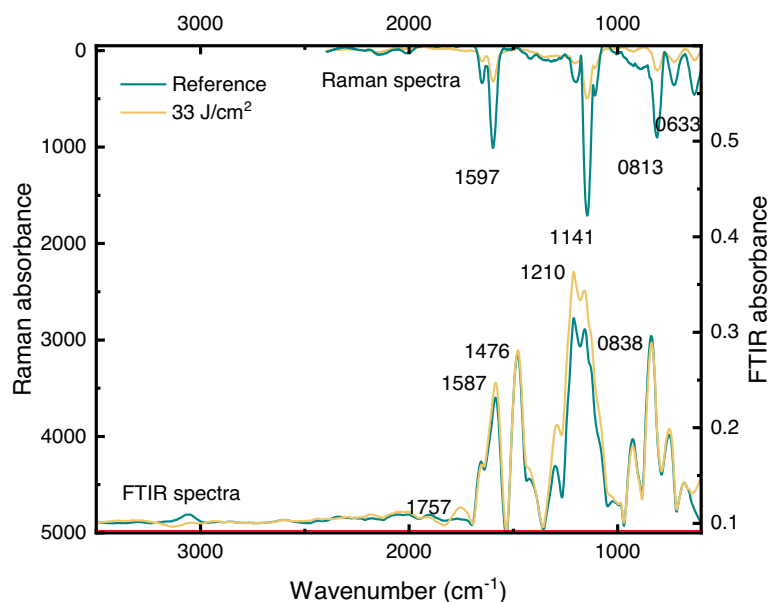


Fig. 3. The effect of UV irradiation on the Raman and FTIR spectra; the sample treated with 33 J/cm² (yellow line) by UV at 110 mW/cm² compared to the unirradiated reference sample (green line) not treated by UV at all. The numbers above the peaks indicate the identified characteristic wavenumbers.

Table 1

Literature-reported changes in Raman spectra due to UV irradiation [57].

Wavenumber (cm ⁻¹)	Bond type	Absorbance (a.u.)	Change in peak intensity due to UV exposure
646	γ_{C-H} bonding out of plane	500	Decreasing
825	γ_{C-H} bonding out of plane	750	Decreasing
1146	Ether γ_{C-O-C} stretching	1750	Decreasing
1595	γ_{C-C} stretching	1000	Decreasing
1651	Carbonyl (C=O)	250	Moderately increasing

Table 2

Literature-reported changes in FTIR spectra due to UV irradiation [58–63].

Wavenumber (cm ⁻¹)	Bond type	Absorbance (a.u.)	Change in peak intensity due to UV exposure
927–800	Aromatic hydrogen C–H	0.3	Moderately decreasing
1200–1100	Aromatic hydrogen C–H	0.3	Moderately decreasing
1100	Ester	0.1	Increasing
1216	Ether C–O–C	0.3	Decreasing
1487	Phenyl	0.25	Decreasing
1800–1650	Carbonyl C=O	0.1	Moderately increasing

quantitative trend, but the recorded images clearly indicate that the surface structure became slightly smoother at the nanoscale after UV irradiation.

Analyzing the UV irradiation specific intensity-dependent structural changes on the surface, distinct differences were observed. The previously mentioned nano-roughness completely disappeared at higher UV intensities (110 and 70 mW/cm²), whereas they remained clearly visible and unchanged at lower UV irradiation specific intensity (50 mW/cm²).

While nanoscale features visually diminished after high-intensity UV exposure, the absence of consistent quantitative roughness trends prevents a direct attribution of the improved resin penetration solely to morphological effects.

3.4. Penetration time as a function of UV irradiation

Results of the penetration experiments are summarized in Supplementary table S3 and depicted in Fig. 8. The accuracy of penetration time measurements was ± 1 s.

According to the measurements, a clear inverse relationship was observed between the UV irradiation specific energy and the total penetration time across all measured temperatures. As the irradiation specific energy increased up to 33 J/cm², the total penetration time consistently decreased, indicating that higher UV exposure significantly accelerates resin penetration along the PEEK surface. This trend suggests that surface oxidation and potential structural changes caused by UV treatment enhance wettability and reduce flow resistance.

The influence of different oxide containing compounds on penetration time is depicted in Fig. 9. As shown in the figure, increasing atomic percentages of carboxyl/carboxylate species correspond to a continuous decrease in penetration time across all investigated temperatures. This reduction is primarily governed by UV irradiation specific energy rather than temperature; the longer the UV exposure, the faster the resin penetration becomes. The most pronounced decrease (–31%) occurred at 40 °C, with slightly smaller but consistent reductions observed at 60 °C (–24.5%) and 80 °C (–26.2%). In all cases, the shortest penetration times were recorded at the highest UV irradiation specific energies, confirming that the UV-induced surface oxidation dominates the impregnation behavior.

According to the previously derived rectangular capillary model in [53], the penetration kinetics follow:

$$x^2 \propto \frac{d}{3 \cdot \eta} \cdot \sigma_{lg} \cdot \cos \theta_h \cdot t$$

indicating that the process is governed by the interfacial term $\sigma_{lg} \cdot \cos \theta_h$. Thus, UV-induced oxidation, by increasing the polarity of the PEEK surface, is expected to reduce the contact angle and enhance the interfacial capillary driving force, which explains the experimentally observed acceleration of resin penetration. Although the contact angle was not directly measured in this study, the clear correlation between surface oxygen concentration and penetration kinetics provides indirect experimental evidence of interfacial energy modification consistent with capillary theory.

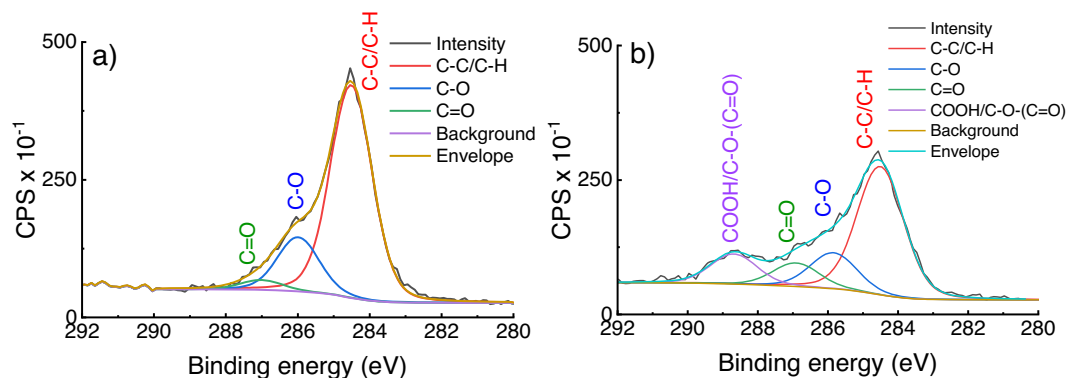


Fig. 4. Deconvolution of the C1s XPS spectra of PEEK for (a) the unirradiated reference and (b) the UV irradiated reference at 33 J/cm² (110 mW/cm²). The measured spectra are fitted with components assigned to different chemical bonds, together with the background and the resulting envelope.

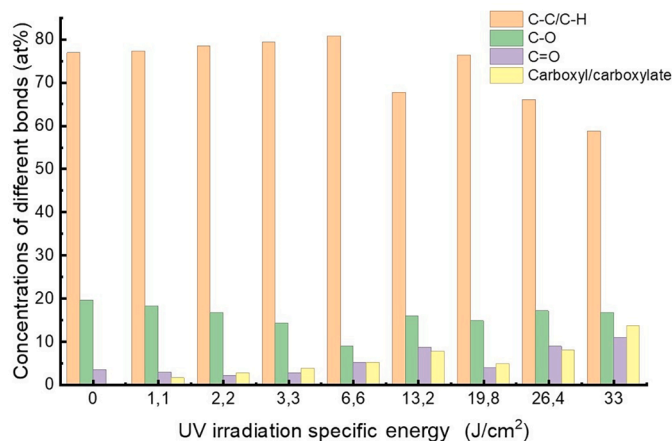


Fig. 5. Concentrations of different bonds of carbon and oxygen species on the surface of PEEK UV-irradiated with 110 mW/cm² UV irradiation specific intensity.

3.5. Dielectric breakdown strength

Results of the dielectric breakdown strength measurements are summarized in Supplementary table S4 and depicted in Figs. 10–11. A

quantitative illustration of the trade-off between penetration and dielectric strength is shown in Fig. 12.

From Fig. 10a) it was found that UV irradiation significantly reduced the dielectric breakdown strength of PEEK insulation. The initial breakdown strength of 101 kV/mm dropped to 88.7 kV/mm (–12%) after exposure to only 1.1 J/cm². This sharp initial drop indicates a threshold-like response at low irradiation doses. However, further increases in UV irradiation specific energy did not result in substantial additional degradation, as shown in Fig. 10a). Fig. 10b) shows that the dielectric breakdown strength is not proportional to the atomic percentage of carboxyl and carboxylate groups formed on the surface. Even at the lowest carboxyl/carboxylate concentration, the dielectric breakdown strength dropped substantially. This suggests that the initial stages of surface oxidation may already modify the near-surface electrical characteristics, rather than exhibiting a simple concentration-dependent trend. UV treatment resulted in an average dielectric breakdown strength of 88.6 kV/mm, regardless of the concentration of carboxyl/carboxylate compounds. This behavior supports a surface-controlled breakdown mechanism, in which the electrically critical state is reached already at low oxidation levels, leading to the observed threshold-like response. The introduction of polar oxygen-containing functional groups may increase local dipole density at the polymer surface and can create shallow trap states within the near-surface region. These electrically active sites can promote charge accumulation and local electric field enhancement, thereby facilitating earlier breakdown initiation even without significant bulk degradation. It should also be

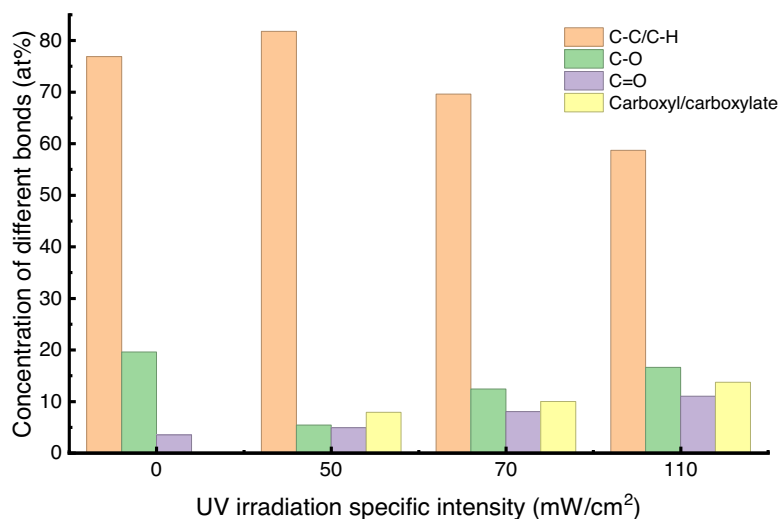


Fig. 6. Concentration of different bonds of carbon and oxygen species on the surface of PEEK as a function of different UV-irradiation specific intensities at 33 J/cm² UV irradiation specific energy.

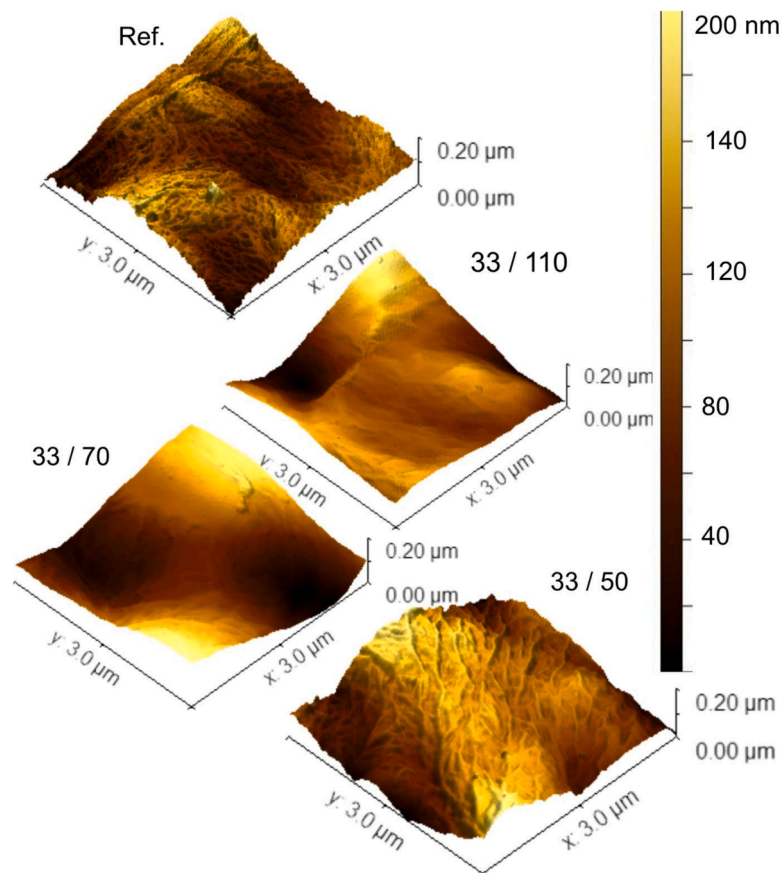


Fig. 7. Surface morphologies of PEEK samples after UV irradiation at different specific energy/intensity levels (J/cm^2 / mW/cm^2), with the images labeled Ref. (unirradiated reference sample), 33/110, 33/70, and 33/50, corresponding to the specific energy/intensity values.

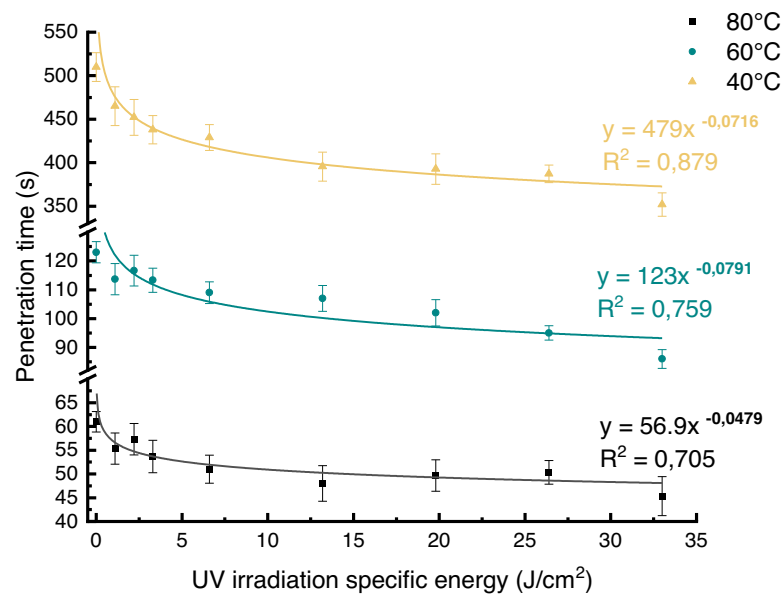


Fig. 8. Measured penetration times at various temperatures as a function of UV irradiation specific energy at UV irradiation specific intensity of $110 \text{ mW}/\text{cm}^2$ (data derived from Supplementary Table S3, Total time).

noted that the breakdown measurements were performed in tap water, and therefore the reported values reflect the combined influence of UV-induced surface oxidation and the ionic test environment.

In contrast, Fig. 11 reveals a clear inverse relationship between dielectric breakdown strength and UV irradiation specific intensity.

Fig. 12 summarizes the relationship between impregnation kinetics and dielectric robustness under identical UV-irradiation conditions, illustrating their non-linear trade-off behavior. Linear trendlines are included only as visual guides.

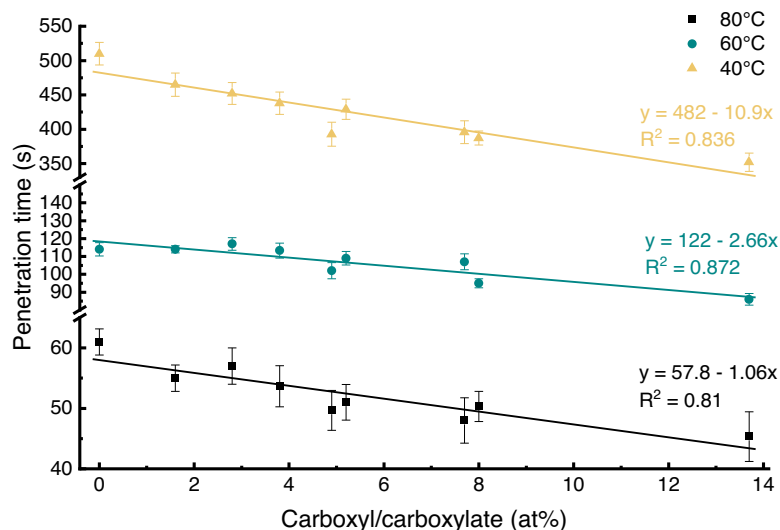


Fig. 9. The influence of concentrations (at%) of carboxyl and carboxylate bonds on the surface of PEEK on the penetration time of epoxy impregnating resin.

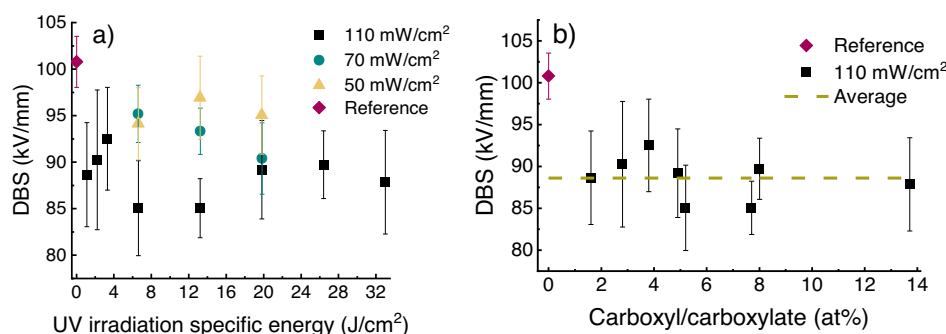


Fig. 10. Effect of UV irradiation on the dielectric breakdown strength (DBS) of PEEK. a) DBS as a function of UV irradiation specific energy b) DBS as a function of carboxyl/carboxylate concentration (at%). The dashed line indicates the average value, and the diamond marker represents the unirradiated reference.

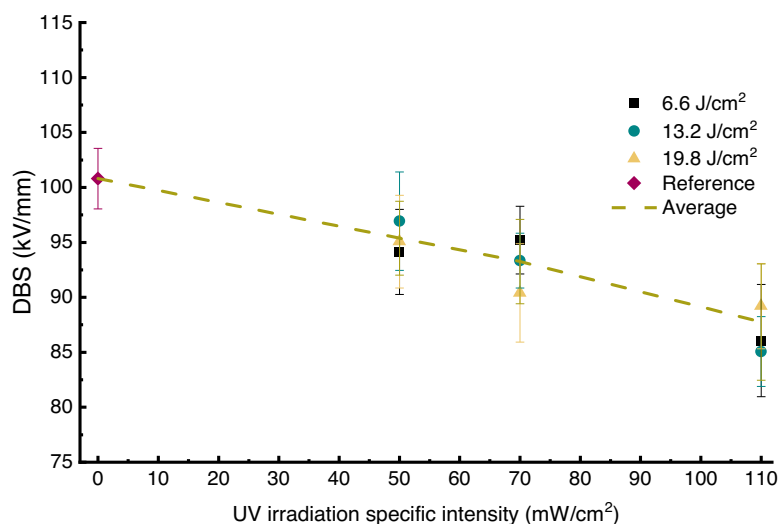


Fig. 11. The effect of UV irradiation specific intensity on the dielectric breakdown strength of PEEK. The diamond marker represents the unirradiated reference.

4. Conclusion

This study establishes a direct correlation between UV-induced surface oxygen concentration and both resin penetration kinetics and

dielectric breakdown behavior in rectangular capillaries formed by PEEK-coated conductors. UV exposure was found to induce oxidation of the PEEK surface, leading to the formation of carbonyl and carboxyl/carboxylate functional groups, as confirmed by FTIR, Raman, and XPS

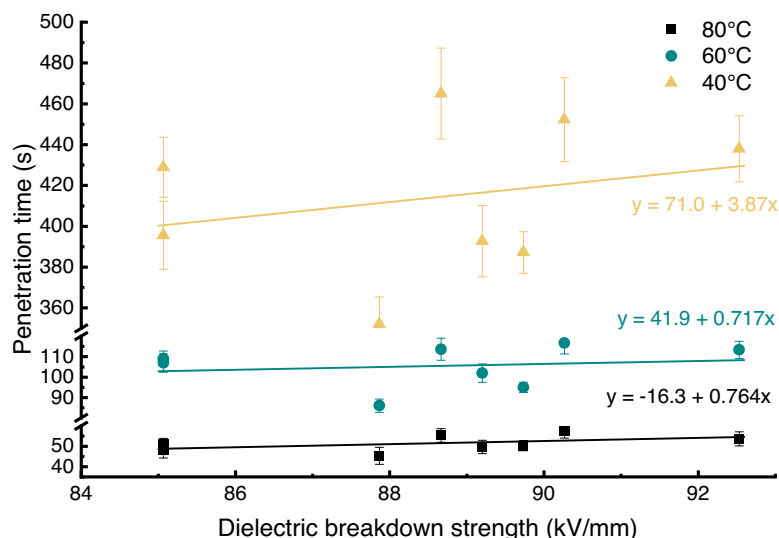


Fig. 12. Relationship between penetration time at different temperatures and dielectric breakdown strength at 110 mW/cm² UV irradiation specific intensity.

analysis.

These surface modifications resulted in faster resin penetration at all tested temperatures. The most significant reduction in penetration time (−31%) was observed at 40 °C. Among the detected chemical species, the atomic percentage of carboxylic and carboxylate groups showed the strongest correlation with improved impregnation rate. Although nanoscale structural changes were observed in the AFM images—specifically the disappearance of nano-roughness after UV exposure—no consistent trend could be confirmed in the quantitative roughness data due to high variability between measurement sites.

At the same time, a reduction in dielectric breakdown strength was also observed, with a 12% drop already present at the lowest UV irradiation specific energy (1.1 J/cm²), which in turn suggests a threshold-like response. Further increases in UV irradiation specific energy resulted in only minor additional losses. These findings suggest that while UV irradiation improves wettability and flow of the impregnating resin, it may also introduce electrically active surface species that compromise dielectric breakdown strength.

The results reveal a clear coupling between UV-induced surface oxidation of PEEK and both resin penetration dynamics and dielectric breakdown strength. The formation of polar oxygen-containing functional groups modifies the interfacial energy and introduces charge-trapping sites, which influence both capillary penetration behaviour and local electric field distribution.

In conclusion, UV surface modification of PEEK may be considered a viable method to improve resin impregnation efficiency—provided that exposure parameters are carefully controlled to avoid excessive deterioration of dielectric properties. While the present results were obtained on simplified laboratory samples, the identified correlations offer fundamental insight into the interfacial mechanisms that govern impregnation and electrical behavior. These insights may support further optimization of insulation systems for automotive applications, where both manufacturing efficiency and long-term reliability are critical. The results also contribute to a deeper understanding of interfacial effects in resin penetration through rectangular micro-capillaries.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, ALK used OpenAI ChatGPT (GPT-5.5) in order to assist with language refinement and stylistic improvement of the English text. After using this tool/service, the author (s) reviewed and edited the content as needed and take(s) full

responsibility for the content of the published article.

CRediT authorship contribution statement

Akos Levente Kokai: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Peter Baumli:** Writing – review & editing, Validation, Supervision, Funding acquisition, Formal analysis. **Zoltán Erdélyi:** Methodology, Investigation. **Tamas Fodor:** Methodology, Investigation. **George Kaptay:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.surfin.2026.109932](https://doi.org/10.1016/j.surfin.2026.109932).

Data availability

Data will be made available on request.

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