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Mechanical acceptability versus material stability in hot-plate-welded PVC-U/glass-fiber composite joints

Marek KOZIELCZYK[1], Kinga MENCEL[2], Jakub KOWALCZYK[1], and Marta PACZKOWSKA[1]*

[1] Faculty of Civil and Transport Engineering, Institute of Machines and Motor Vehicles, Poznan University of Technology, Poznan, Poland
[2] Faculty of Mechanical Engineering, Institute of Material Technology, Poznan University of Technology, Poznan, Poland

Abstract. This study assesses the material integrity of hot-plate-welded unplasticized PVC profiles reinforced with glass-fiber composite inserts, focusing on whether cycle shortening preserves the weld-zone state beyond satisfying macroscopic strength criteria. The constituent materials were characterized to define the mechanical and thermomechanical mismatch of the hybrid system. Welded corner specimens were produced under selected parameter sets and examined by ball indentation hardness testing, stereomicroscopy, differential scanning calorimetry, and Fourier-transform infrared spectroscopy in attenuated total reflectance mode. The composite contained 52.25 wt.% glass fiber and showed higher stiffness, strength, and heat deflection temperature than PVC-U, but substantially lower deformability, confirming pronounced material asymmetry in the joint region. The weld produced at 264°C for 22 s exhibited a material response comparable to the reference condition of 264°C for 30 s. Hardness, microscopy, DSC, and FTIR-ATR revealed no detectable microstructural, thermal, or chemical deterioration after reducing plasticization time from 30 s to 22 s. Conversely, although the 270°C/21 s variant remained mechanically acceptable in terms of the failure-load criterion, it showed light-brown discoloration extending from the bead into the joint interior, lower weld-zone hardness, and a broader DSC response, indicating local thermal overexposure. These results show that mechanical acceptability does not necessarily imply material stability and that cycle-time reduction should therefore be evaluated using complementary mechanical, morphological, thermal, and chemical criteria.

Keywords: glass-fiber composite; hot-plate welding; weld-zone integrity; processing window; FTIR-ATR; PVC-U.

1. INTRODUCTION

Thermoplastic welds are increasingly evaluated not only in terms of final load-bearing capacity, but also through the mechanisms and quality of interface formation [1]. In fiber-reinforced thermoplastic composites, weld quality is additionally linked to heat generation and joint-formation mechanisms [2]. Manufacturing conditions can influence the quality and mechanical response of welded thermoplastic composite joints [3]. Processing of thermoplastic composites can also generate residual stresses that affect structural performance [4]. In addition, excessive thermal exposure during welding may lead to degradation of temperature-sensitive constituents [5].

This perspective is particularly relevant to thermoplastic composites and hybrid structures. Fusion bonding requires appropriate softening of the thermoplastic matrix and formation of an effective joining interface [1]. In fiber-reinforced thermoplastics, local heat generation and intimate contact formation are essential elements of joint development [2]. The resulting joint properties are also influenced by manufacturing conditions and the consolidation process [3]. When one constituent of the system is a fiber-reinforced composite, the problem becomes more complex because manufacturing-induced heterogeneity can influence local joint quality and mechanical response [3]. Differences in the thermomechanical properties of composite constituents can promote the development of residual stresses during processing [4]. High local thermal exposure can further increase the risk of material degradation during welding [5]. In PVC profiles, pultruded thermoplastic composite reinforcements can provide both structural and thermal benefits compared with conventional reinforcement concepts [6]. At the same time, the preparation and machining of the composite insert directly affects the strength of the welded joint [7].

Hot-tool welding has been successfully applied to PVC, with the resulting weld performance depending on the formation of an effective welded joint [8]. More generally, hot-plate welding requires process-specific optimization because a single universal parameter setting is not suitable for different materials and joint requirements [9]. Heating and other process parameters can influence susceptibility to stress cracking [10]. Welding parameters and the associated thermal history can also modify weld-zone morphology and mechanical behavior [11]. In fiber-reinforced thermoplastics, interface geometry additionally influences the resulting joint strength [12]. For a hybrid PVC-U and glass-fiber composite system, these effects mean that the relevant question is not only whether the weld satisfies technological requirements, but also whether the local weld-zone material remains stable under the applied thermal conditions.

For this reason, in a hybrid PVC-U and glass-fiber composite system, it is insufficient to ask only whether the weld has

*e-mail: marta.paczkowska@put.poznan.pl

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been produced correctly from a technological standpoint. The more consequential question is whether, under a given thermal path, the weld zone retains material continuity and stability, or whether it has already entered a regime of local thermal overexposure.

For PVC, an additional limitation arises from the chemistry of the polymer itself. Thermal degradation of PVC proceeds primarily through dehydrochlorination and the development of conjugated polyene sequences [13]. FTIR spectroscopy can reveal decomposition-related changes through modifications of characteristic absorption bands and the appearance of bands associated with unsaturated structures [14]. Broader studies of PVC thermal degradation further confirm the importance of dechlorination and subsequent degradation pathways [15].

This is important for the interpretation of the weld zone because the boundary between proper plasticization and the onset of undesirable chemical transformations does not necessarily become immediately apparent in simple mechanical tests. Recent thermal-ageing studies on rigid PVC have identified structural changes using FTIR and DSC, including effects associated with dehydrochlorination and chain modification [16]. More recent work on unplasticized PVC exposed to heat and humidity has shown that spectroscopic evidence of degradation and visible discoloration can develop without a correspondingly pronounced deterioration in mechanical properties [17].

Consequently, the visual assessment of the weld face or the value of the failure load alone is not sufficient for PVC welds when the objective is to define a reliable safe processing window.

Against this background, the literature on welded PVC profiles remains relatively narrowly oriented towards technological and functional performance. Previous studies on PVC window profiles examined the influence of welding parameters on the strength of welded corners [18]. Other work focused on manufacturing quality and the influence of welding conditions, including temperature control, on the quality of PVC frames [19]. For profiles containing a composite insert, previous work established the influence of composite milling depth on weld strength [7]. The combined influence of milling depth and welding-head feed rate on weld strength, continuity, and symmetry was subsequently examined [20]. A further study addressed the effect of melting time together with composite milling depth on failure load, dimensional conformity, and process quality [21]. Welding temperature was then investigated in relation to the durability and quality of composite-reinforced window-profile joints [22]. These studies primarily addressed technological and mechanical performance rather than the combined microstructural, thermal, and chemical response of the weld zone. Accordingly, the novelty of the present work lies not in the design of the composite insert itself, but in the combined assessment of mechanical acceptability and local material stability of the hybrid weld zone using complementary mechanical, microscopic, thermal, and spectroscopic methods. In parallel, recent work demonstrates the growing relevance of pultruded thermoplastic reinforcements in PVC profiles, although primarily in relation to the structural and thermal function of the reinforcement, not to the material state of the hybrid region after welding [6]. As a result, it remains insufficiently understood how the pronounced asymmetry of the PVC-U and glass-fiber composite system affects the local response of the weld zone and where the practical boundary lies between a stable material state and the onset of degradation.

For this reason, the hybrid PVC-U and composite weld zone should be treated not as a passive consequence of the process, but as a local region of material response controlled simultaneously by constituent asymmetry and by the thermal history of welding. In this study, weld-zone material integrity is defined operationally as the preservation of the local mechanical, morphological, thermal, and chemical state of the PVC-U-rich weld region relative to the reference welding condition. It is not represented by a single parameter, but by the convergence of evidence from hardness testing, microscopy, DSC, and FTIR-ATR, with no detectable deterioration relative to the reference condition within the sensitivity of the applied methods. In the present work, this problem was examined from a materials-science perspective by combining the characterization of constituent-property asymmetry with local hardness measurements, microscopic observation, and DSC and FTIR-ATR analysis of the weld zone. The aim was to determine whether reducing the plasticization time to 22 s at 264°C allows the weld zone to retain a material state comparable to that obtained under the reference condition of 264°C for 30 s, and whether the variant produced at 270°C for 21 s already marks a practical degradation boundary for PVC. Framed in this way, the research problem shifts the emphasis from routine process optimization to the relationship between the processing window and the structural, thermal, and chemical stability of the hybrid weld zone. From a practical perspective, the proposed assessment helps to distinguish welding conditions that are mechanically acceptable from those that also preserve the local material state of the weld zone, thereby supporting a more reliable selection of processing parameters for industrial PVC-U/composite profiles.

2. MATERIALS AND METHODS

2.1. Materials

The study was conducted on a six-chamber PVC-U window profile incorporating two glass-fiber composite reinforcing inserts. The composite inserts were not manufactured as part of this study and were investigated as finished industrial components in the as-received condition, while their manufacturing process was outside the scope of the present work. The insert was therefore not selected as an independent experimental variable but constituted the reinforcing element of the investigated industrial profile. The profile had a nominal width of 70 mm and an installation depth of 85 mm. This profile configuration was selected as an industrially manufactured system available for the experimental program, while the profile geometry and number of chambers were treated as fixed characteristics rather than experimental variables. The weld width was not treated as an independent experimental variable. During welding, the full-frontal cross-sections of the profile ends were joined, while the resulting weld-bead geometry developed from material softening and displacement during the welding cycle. The geometry of the investigated profile and the location of the composite inserts

are shown in Fig. 1. To interpret the behavior of the hybrid weld zone, the constituent materials, i.e., the PVC-U profile material and the reinforcing composite, were first characterized separately, after which the welded-corner specimens were examined using a dedicated set of material-sensitive methods.

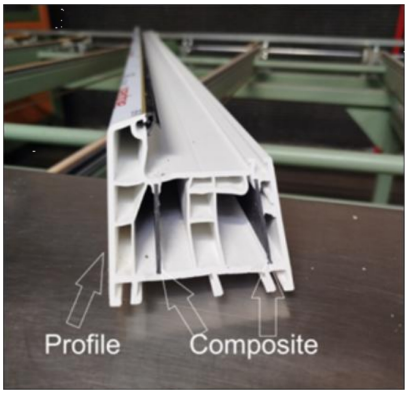


Fig. 1. Profile view with composite inserts

The quantitative experimental results were summarized using mean values and 95% confidence intervals. For weld-zone hardness, each welding condition was assessed using three independent welded specimens, with a total of 12 indentation measurements obtained for each condition. The confidence intervals were used to express the uncertainty of the mean values and to support comparison between the investigated welding conditions.

For the present study, material integrity was assessed comparatively with respect to the reference weld condition rather than by means of a single absolute threshold. Hardness was used to identify changes in the local mechanical response of the weld material, with a systematic decrease beyond the experimental variability treated as an indication of deterioration. Microscopy was used to identify morphological or visual features associated with thermal overexposure, including discoloration and cracking. DSC was used as a supporting method to identify reproducible changes in the thermal response of the weld material, particularly in the glass-transition-related region relative to the reference condition. FTIR-ATR was used to assess chemical stability through the persistence and positions of the characteristic PVC-U absorption bands. The appearance of new reproducible bands or the disappearance of diagnostic bands would be treated as evidence of chemical alteration. Material integrity was considered preserved when the combined results showed no detectable mechanical, morphological, thermal, or chemical deterioration relative to the reference condition within the sensitivity of the applied methods.

2.2. Constituent-level characterization of PVC-U and composite insert

The baseline experimental program comprised impact, tensile, flexural, hardness, fiber-content and thermomechanical testing of the PVC-U profile material and of the reinforcing composite. The purpose of this stage was to establish the mechanical and thermal asymmetry of the hybrid system prior to welding.

Charpy impact tests were performed on rectangular notched and unnotched specimens in accordance with PN-EN ISO 179-1:2023-11 at ambient temperature using a ZwickRoell Charpy HIT25P pendulum impact tester (ZwickRoell GmbH & Co. KG, Ulm, Germany). The nominal impact velocity was 2.901 m/s, and the pendulum mass was 1.188 kg. Rectangular specimens with dimensions of $80 \times 10 \times 3$ mm were tested. Five PVC-U specimens and five composite specimens were examined.

Static tensile tests were performed in accordance with PN-EN ISO 527-2:2025-12 using a ZwickRoell Z010 universal testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany) at a crosshead speed of 50 mm/min under ambient conditions. Ten rectangular PVC-U specimens and ten composite specimens, each measuring $150 \times 20 \times 3$ mm, were tested. The stress-strain curves were used to determine the elastic modulus, tensile strength, strain at maximum stress and elongation at break.

Three-point bending tests were performed in accordance with PN-EN ISO 178:2019-06 on rectangular specimens of $100 \times 10 \times 3$ mm. The tests were conducted on a ZwickRoell Z010 machine using a crosshead speed of 5 mm/min for PVC-U and 20 mm/min for the composite. Nine measurements were performed for each material.

Ball indentation hardness measurements of the constituent materials were conducted in accordance with PN-EN ISO 2039-1:2004 using a KB Prüftechnik GmbH KB150R hardness tester (Hochdorf-Assenheim, Germany). A hardened steel ball indenter with a diameter of 5 mm and a test load of 358 N were used. The test load was maintained for 30 s. Hardness was determined from the measured indentation depth in accordance with the standard procedure and expressed in N/mm^2. Five PVC-U specimens and five composite specimens, each measuring $80 \times 10 \times 3$ mm, were tested, with two measurements performed on each face of every specimen.

The glass-fiber mass fraction in the reinforcing composite was determined using two composite specimens. The specimens were weighed, placed in crucibles, conditioned in a furnace at 800°C for 2 h, and then reweighed together with the residue. This procedure was used to determine the residual fiber fraction after thermal removal of the matrix.

The thermal response of the constituent materials was assessed by Vicat softening temperature measurements for PVC-U and by heat deflection temperature (HDT) measurements for both PVC-U and the composite. The Vicat softening temperature was determined for two PVC-U specimens using a controlled heating rate of 50°C/h starting from 20°C. HDT measurements were performed in accordance with ISO 75 on PVC-U specimens ($n = 3$) and composite specimens ($n = 3$), using 0.45 kg weights, a heating rate of 50°C/h, a support span of 64 mm, and a methyl silicone oil bath.

2.3. Weld specimens and analyzed process variants

The weld-zone study was performed on welded corner specimens representing five predefined process variants. The selected variants are listed in Table 1. In the analyzed series, the welding-head feed rate was constant, whereas the welding temperature, melting time, and composite milling depth varied between the individual weld types.

Table 1
Selected weld variants obtained under different process parameters

Parameter	(a)	(b)	(c)	(d)	(e)
Welding temperature [°C]	256	263	264	264	270
Melting time [s]	30	22	22	30	21
Composite milling depth [mm]	1.0	1.0	1.0	0.0	1.0
Welding-head feed rate [mm/s]	0.25	0.25	0.25	0.25	0.25

The 264°C/30 s condition was used as the reference process condition. However, because this variant was produced without composite milling, whereas the 264°C/22 s variant used a milling depth of 1.0 mm, their comparison should be interpreted as a comparison between two process variants rather than as an isolated assessment of the effect of melting time.

2.4. Hardness measurements of the weld zone

Ball indentation hardness testing of the welded-joint specimens was performed in accordance with PN-EN ISO 2039-1:2004 for all five weld variants using a 5 mm hardened steel ball indenter, a test load of 358 N, and a load application time of 30 s. Hardness was determined from the measured indentation depth in accordance with the standard procedure and expressed in N/mm^2. Each process variant was assessed on three welded specimens. Measurements were taken at two locations on each side of the corner, i.e., two points per side of the weld, which yielded a total of 12 measurements for each weld type. The measurements were recorded using a KB Prüftechnik GmbH KB150R hardness tester.

2.5. Microscopic examination of the weld region

Microscopic examination of the welds was performed using an Opta-Tech SK-series stereomicroscope (OPTA-TECH, Warsaw, Poland). The instrument enabled three-dimensional observation of the weld bead and adjacent material regions under reflected and/or transmitted light. Observations were conducted with WF10×/20 eyepieces over a magnification range of $7\times - 45\times$, and the zoom was selected depending on the local weld feature under assessment. The stereomicroscopic examination was qualitative and was used to assess weld morphology and visible signs of thermal overexposure. No quantitative porosity assessment was performed. The microscopy program covered all five weld variants listed in Table 1.

2.6. Differential scanning calorimetry

Differential scanning calorimetry was used to compare the thermal response of the weld material after normalization of the prior thermal history. The second heating run was selected for comparative interpretation because the first heating can include reversible effects associated with the thermal and thermomechanical history of the as-welded material. The first heating followed by controlled cooling provided a common thermal history for the investigated specimens before the second heating. Consequently, the second-heating results were used to identify persistent differences in the thermal response of the weld material rather than to reconstruct directly the thermal history introduced during welding. Specimens weighing 10 ± 0.20 mg were weighed on a RADWAG XA52/2X balance (RADWAG, Radom, Poland) with 0.01 mg resolution and placed in aluminum pans. The DSC specimens were collected from the central part of the weld bead, corresponding to the weld region visible in Fig. 3. At least two specimens originating from independent welded joints were analyzed for each welding condition. DSC measurements were collected using a Netzsch DSC 204F1 Phoenix instrument (NETZSCH-Gerätebau GmbH, Selb, Germany).

A heating–cooling–heating program was applied. The second heating run was intentionally selected for comparative interpretation because the first heating may contain reversible effects associated with the previous thermal and thermomechanical history of the as-welded material. The first heating followed by controlled cooling was therefore treated as a conditioning stage that imposed a common thermal history on all investigated specimens. Consequently, the second-heating results were used to identify persistent differences in the thermal response of the weld material rather than to directly reconstruct the thermal history introduced during welding. The program consisted of heating from 20°C to 130°C at 10°C/min under nitrogen, holding at 130°C for 10 min, cooling from 130°C to 20°C at 10°C/min under nitrogen, and holding at 20°C for 10 min. This sequence was repeated twice. The glass-transition temperature, Tg, was determined from the inflection point corresponding to the maximum slope of the Cp step. When this value was unavailable from the software, Tg was taken as the midpoint temperature of the heat-capacity step during the second heating. All five weld variants were analyzed using this procedure.

2.7. Fourier-transform infrared spectroscopy in attenuated total reflectance mode

The chemical character of the constituent materials and of the weld zone was examined by Fourier transform infrared spectroscopy in ATR mode. FTIR measurements were performed using a Jasco FT/IR-4600 spectrometer (JASCO Corporation, Hachioji, Tokyo, Japan) equipped with a TGS detector and an ATR PRO ONE accessory operated at a 45° angle of incidence. Spectra were collected over approximately 4000–400 cm^{-1} with a resolution of 4 cm^{-1} using 60 or 40 co-added scans.

The FTIR program included five PVC-U profile specimens and two specimens of the reinforcing composite, with four spectra recorded for each specimen. In addition, the five weld variants listed in Table 1 were examined. For the weld-zone analysis, specimens were collected from the central part of the weld bead, corresponding to the weld region visible in Fig. 3. Two specimens originating from two independent welded joints were analyzed for each welding condition. Because ATR measurements are sensitive to specimen–crystal contact, surface roughness and local topography, the interpretation was focused primarily on the persistence, position, and qualitative consistency of characteristic absorption bands rather than on direct comparison of absolute band intensities.

3. RESULTS AND DISCUSSION

3.1. Constituent asymmetry of the PVC-U and composite system

The constituent-level results revealed a pronounced mechanical and thermomechanical asymmetry between the PVC-U profile material and the glass-fiber-reinforced composite insert. The composite contained approximately 52.25 wt.% glass fiber and exhibited a clearly reinforcement-dominated response, with a tensile modulus of 5854 MPa and a tensile strength of 88 MPa, compared with 2022 MPa and 45 MPa, respectively, for PVC-U. At the same time, the elongation at break decreased from 42% for PVC-U to 3% for the composite, indicating that the increase in stiffness and load-bearing capacity was accompanied by a substantial loss of deformability. A similar trend was observed in bending, where the composite reached a flexural modulus of 13.4 GPa and a flexural strength of 122 MPa, whereas PVC-U reached 3.4 GPa and 46 MPa. These results show that the insert cannot be treated as mechanically neutral reinforcement. Instead, it introduces a strong mismatch in stiffness and strain tolerance within the hybrid joint region.

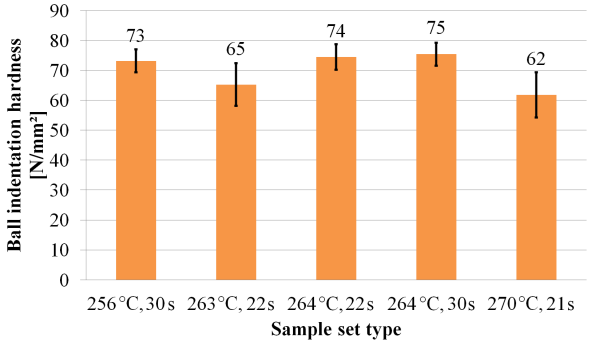
The impact and thermal data reinforce the same interpretation. In the unnotched condition, the composite reached 25 kJ/m^2, whereas the notched composite dropped to 6 kJ/m^2, compared with 15 kJ/m^2 for notched PVC-U, which indicates a higher notch sensitivity of the fiber-reinforced insert. Thermally, the most relevant contrast concerns the heat deflection temperature: PVC-U reached 73°C, whereas the composite reached 202°C, despite the Vicat softening temperature of PVC-U remaining in the range of 89–90°C. This means that, under the heating and pressure conditions relevant to welding, PVC-U loses functional stiffness much earlier than the composite insert. In practical terms, the weld zone becomes an interaction region between a plastifying polymer phase and an adjacent reinforcement that remains comparatively rigid over the same temperature interval. This asymmetry provides the material basis for the sensitivity of weld formation to thermal exposure and explains why the integrity of the joint zone cannot be inferred from strength criteria alone.

3.2. Weld-zone response under selected welding conditions

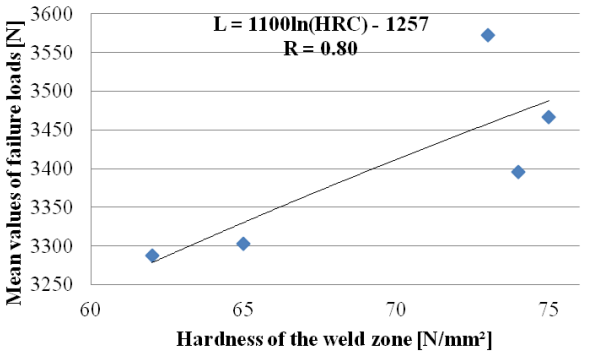
The weld-zone study was therefore interpreted against this background of constituent mismatch. Within the selected experimental set, the most relevant comparison is that between the optimized condition of a welding temperature of 264°C, a melting time of 22 s, a composite milling depth of 1.0 mm, and a welding-head feed rate of 0.25 mm/s, and the reference condition of a welding temperature of 264°C, a melting time of 30 s, no composite milling, and a welding-head feed rate of 0.25 mm/s, with the boundary condition of a welding temperature of 270°C, a melting time of 21 s, a composite milling depth of 1.0 mm, and a welding-head feed rate of 0.25 mm/s included as a thermally overloaded case. The pilot-stage findings showed that 264°C with a melting time of 22 s and a composite milling depth of 1.0 mm constitutes a practically stable processing window, whereas further reduction of melting time to 21 s requires thermal intensification that leads to unacceptable bead discoloration and loss of process robustness.

The pilot-stage failure-load results were used only as mechanical context for the material-sensitive analysis. Although the investigated welds generally retained a substantial load-bearing reserve relative to the minimum admissible failure load, the mechanical response alone was not used to define the processing boundary. Dimensional conformity, weld-bead appearance, process stability, and the material state of the weld zone were considered jointly in assessing process acceptability.

Ball indentation hardness results for all five welding conditions are summarized in Fig. 2a as mean values with 95% confidence intervals. Welds produced between 256°C and 264°C showed mean hardness values of approximately 65–75 N/mm^2, whereas the 270°C/21 s variant showed the lowest mean value of approximately 62 N/mm^2. The 95% confidence intervals for the 264°C/22 s and 264°C/30 s variants overlapped, indicating no clear separation between these two conditions at the hardness level. At the same time, all welds were softer than the parent PVC-U material, whose mean hardness was approximately 88 N/mm^2. This reduction is consistent with the local thermal history of the joint zone and may be treated as a typical consequence of plasticization and re-solidification during weld formation rather than as evidence of degradation. By contrast, the boundary variant produced at 270°C and 21 s exhibited a



(a)



(b)

Fig. 2. Weld-zone hardness results for the investigated welding conditions: (a) mean ball indentation hardness with 95% confidence intervals, and (b) relationship between mean failure load and ball indentation hardness of the weld zone

lower mean hardness of 62 N/mm^2, which indicates a less stable joint-zone material state. The 264°C/22 s and 264°C/30 s conditions showed comparable mean ball indentation hardness values, and their 95% confidence intervals overlapped. This indicates that no clear separation between these two process variants was resolved at the hardness level within the observed experimental variability. However, because the two variants also differed in composite milling depth, this comparison should not be interpreted as an isolated effect of melting time. The hardness results therefore provide supporting information on the local mechanical state of the weld, but they should be interpreted together with the microscopic, thermal, and chemical characterization.

Microscopy provided the clearest structural discrimination between acceptable and unacceptable weld-zone states (Fig. 3).

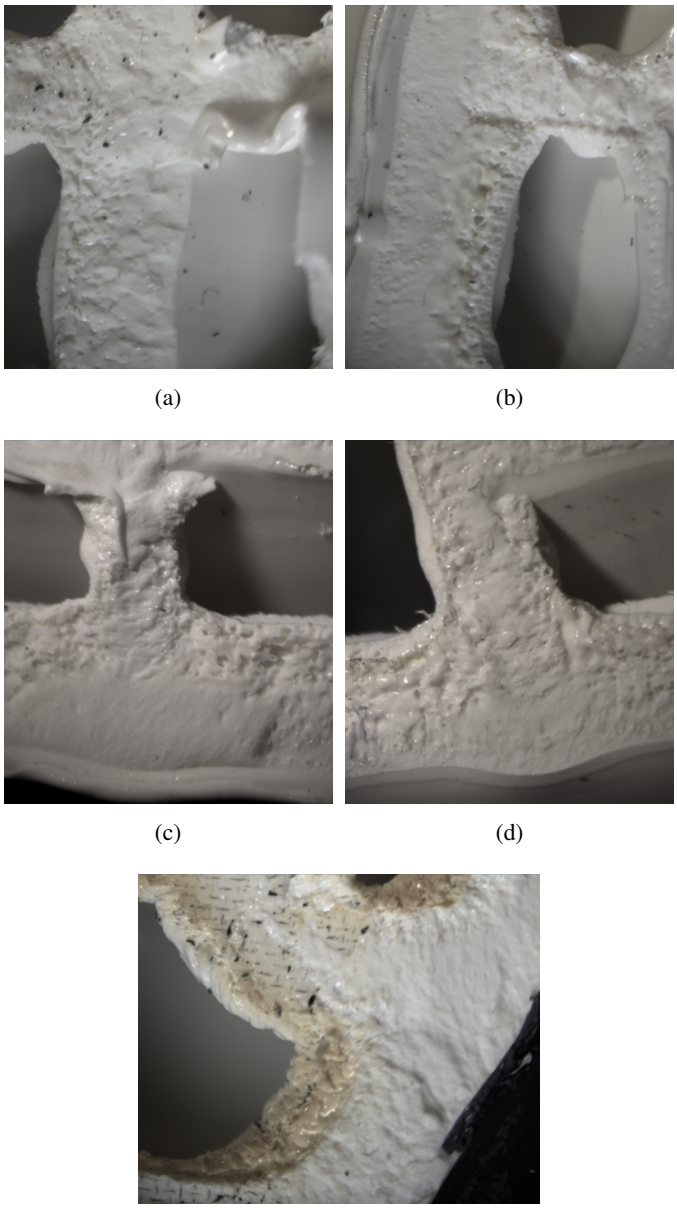


Fig. 3. Recorded images of weld structures for the individual welding-parameter variants (a)–(e), as specified in Table 1

For the welds produced within 256–264°C, the weld bead remained light in color and the joint morphology, although uneven, did not show visible features indicative of PVC degradation. In contrast, the specimen welded at 270°C for 21 s exhibited a light-brown discoloration extending from the bead into the joint interior, which was interpreted as an indication of local thermal overexposure of the PVC-U weld material. This observation is particularly important because the same boundary condition could still produce failure-load levels above the minimum acceptable threshold in the earlier process study [7, 20–22]. The microscopy therefore demonstrates that a joint may appear mechanically acceptable at a screening level while already exhibiting signs consistent with local thermal overexposure within the heat-affected region. The present results do not establish a direct quantitative relationship between discoloration and failure load. Discoloration is therefore treated here as a qualitative indicator of local thermal overexposure rather than as a predictor of load-bearing capacity.

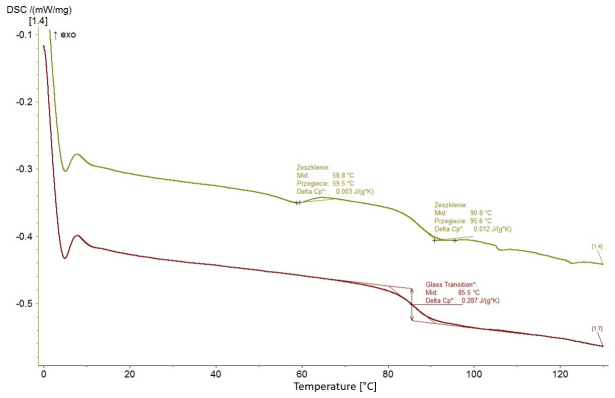
3.3. Thermal and chemical evidence of weld-zone stability

The DSC comparison presented below is based on the second heating run. Accordingly, the observed differences are interpreted as persistent differences in thermal response after a common thermal treatment, rather than as direct signatures of the original thermal history generated during welding.

Across the analyzed welds, the second-heating thermograms were dominated by glass-transition-related features in the range from 20°C to 130°C, with no melting or crystallization peaks. The most complex traces were observed for the welds produced at 264°C with melting times of 22 s (Fig. 4a) and 30 s (Fig. 4b), where a weak lower-temperature effect around 55−60°C coexisted with a dominant transition near 85−86°C and weaker features between approximately 90°C and 95°C. By contrast, the series welded at 263°C for 22 s and 256°C for 30 s showed transitions more tightly clustered within roughly 88−95°C, while the boundary case of 270°C for 21 s (Fig. 4c) showed a broad bimodal transition concentrated near 86−90°C and 94°C.

The thermograms provide no basis to claim that welding at 264°C for 22 s induces a material reorganization of the amorphous phase that is qualitatively different from that observed at 264°C for 30 s. The main transition near 85−86°C remained relatively repeatable across both series, whereas the subsidiary features were weak and likely affected by residual stresses, local additive heterogeneity, and the thermomechanical history imposed during welding. In other words, DSC suggests local structural complexity within the amorphous phase, but it does not support a conclusion of distinct weld-zone transformation caused by shortening the melting time from 30 s to 22 s at the same welding temperature.

FTIR-ATR provided the strongest evidence regarding the chemical stability of the weld zone. The spectra of the base materials were internally consistent and confirmed a PVC matrix in the profile material and a polyester-type matrix in the composite insert, the latter identified inter alia by the carbonyl band in the region of about 1700–1730 cm^{-1}. Most importantly, direct comparison of the welds produced at 264°C with melting times of 22 s and 30 s (Fig. 5a) revealed neither the appear-



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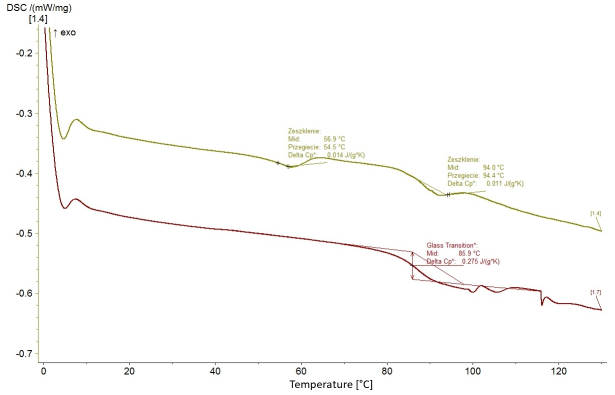

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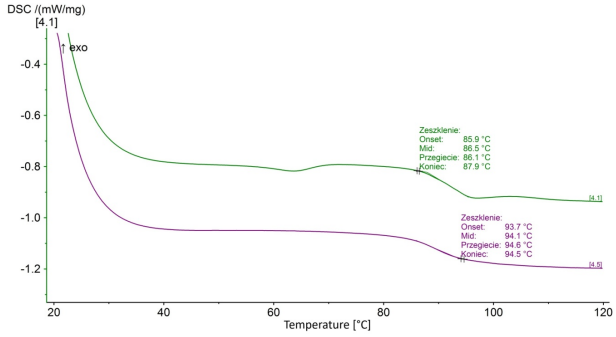
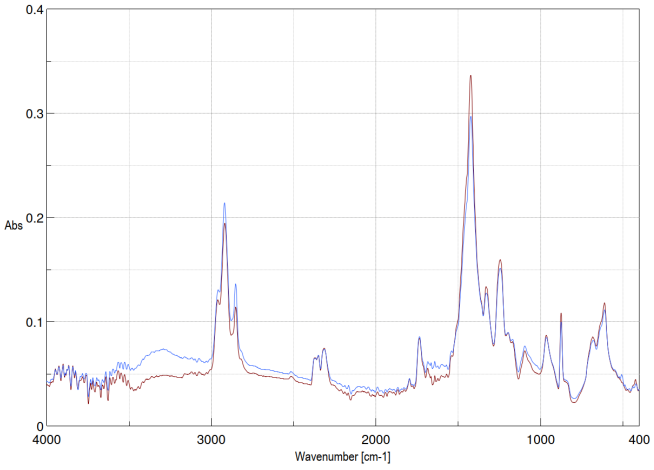


(c)

Fig. 4. DSC thermogram of the PVC weld specimen produced at: (a) welding temperature of 264°C and a melting time of 22 s; (b) welding temperature of 264°C and a melting time of 30 s; (c) welding temperature of 270°C and a melting time of 21 s

ance of new bands nor the disappearance of diagnostic bands. The fingerprint-region core remained concordant, providing no detectable evidence of a change in the chemical character of the weld-zone material after shortening the melting time. Any observed local spectral differences (Fig. 5b) are more plausibly attributed to ATR contact conditions, surface roughness, and local topography than to genuine chemical transformation.



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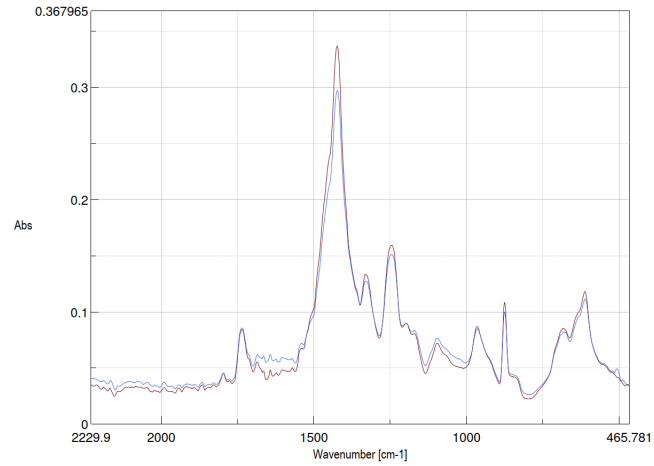

(b)

Fig. 5. FTIR-ATR spectral comparison of weld specimens produced at: (a) 264°C for 22 s and 264°C for 30 s over the range 4000–400 cm^{-1} and (b) 264°C for 22 s and 264°C for 30 s over the range 2230–464 cm^{-1}

3.4. Implications for safe processing of the hybrid weld

Taken together, the results form a coherent materials-based chain of evidence. First, the constituent materials were shown to differ sharply in stiffness, strength, deformability, and thermomechanical stability. Second, the 264°C/22 s process variant showed no detectable deterioration in hardness, no microscopy-visible indication of degradation, no distinct DSC response relative to the 264°C/30 s reference condition, and no detectable change in the FTIR fingerprint of the weld material within the sensitivity of the applied methods. Because the two variants also differed in composite milling depth, these observations should not be interpreted as evidence of an isolated effect of melting time. From an industrial perspective, the shorter 22 s plasticization stage reduces the duration of heating and may contribute to a shorter welding cycle, provided that the required joint performance and weld-zone material stability are maintained. Third, the boundary condition of 270°C with a melting time of 21 s showed that

attempts to compensate for further time reduction by increasing temperature led to a qualitatively different outcome, namely visible discoloration penetrating the weld region and a concurrent decrease in hardness.

The central implication is that the hybrid PVC-U and composite system must be assessed through joint-zone material integrity, not only through technological acceptability or failure-load metrics [7, 20–22]. The optimized condition of 264°C and 22 s preserves weld-zone quality at a level comparable to that of the 264°C and 30 s reference, while the transition to 270°C and 21 s crosses a practical degradation boundary. This finding has greater interpretive value than the mere identification of optimal process parameters, as it directly relates the processing window to the structural, thermal, and chemical stability of the hybrid weld zone.

4. CONCLUSIONS

The present study demonstrates that the investigated PVC-U profile reinforced with a glass-fiber composite insert should be regarded as a mechanically and thermomechanically asymmetric hybrid system, rather than as a conventional PVC-U profile containing a passive reinforcement. The composite insert, which contained approximately 52.25 wt.% glass fiber, exhibited substantially higher stiffness, strength, and thermal resistance than the PVC-U matrix, while also showing markedly lower deformability. This contrast in constituent properties means that the weld zone is a local interaction region between a plasticized thermoplastic phase and an adjacent reinforcement that remains comparatively rigid under the same thermal exposure.

Within this material framework, the weld produced at 264°C for 22 s, with a composite milling depth of 1.0 mm, exhibited a weld-zone response comparable to that obtained under the reference condition of 264°C for 30 s. The hardness measurements, microscopic observations, DSC traces, and FTIR-ATR spectra did not indicate any qualitative deterioration of the weld-zone material caused by reducing the plasticization time from 30 to 22 s at the same welding temperature. These results indicate that the 264°C/22 s process variant shows no detectable loss of weld-zone material integrity within the sensitivity of the applied methods, rather than merely satisfying a macroscopic criterion of process acceptability.

The variant produced at 270°C for 21 s revealed the practical limit of further cycle shortening through an increase in welding temperature. Although this condition may still appear acceptable when assessed only through selected technological or strength-related criteria, microscopic observations showed light-brown discoloration extending from the weld bead into the joint interior. This indicates local thermal overexposure of PVC-U and confirms that load-bearing assessment alone is insufficient for a reliable evaluation of hybrid welded joints.

From a scientific perspective, the results indicate that the acceptability of a welded hybrid PVC-U/composite joint is governed by a coupled process–material mechanism. The mechanical response, expressed by the mean failure load, provided an important measure of technological performance but did not, by itself, define the safe processing boundary. Instead, the boundary emerged only when the mechanical response was interpreted together with weld-zone hardness, microscopic evidence of discoloration, DSC response, and FTIR-ATR chemical stability. This integrated interpretation shows that the processing window of the investigated hybrid joint is controlled by the balance between PVC-U plasticization, composite-insert constraint, local thermal exposure, and preservation of the PVC-U-rich weld-zone material.

Overall, the results demonstrate that mechanical acceptability alone is insufficient to define the safe processing boundary of the investigated hybrid joint. The principal contribution of this work is the demonstration that the 264°C/22 s process variant can provide a weld-zone material response comparable to that obtained for the 264°C/30 s reference condition, with no detectable deterioration within the sensitivity of the applied methods. The combined assessment of mechanical and material responses therefore provides a basis for distinguishing between mechanically acceptable and materially stable welded joints.

REFERENCES

[1] C. Ageorges, L. Ye, and M. Hou, "Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review," *Compos. Part A Appl. Sci. Manuf.*, vol. 32, no. 6, pp. 839–857, 2001, doi: 10.1016/S1359-835X(00)00166-4.

[2] Y. Wang, Z. Rao, S. Liao, and F. Wang, "Ultrasonic welding of fiber reinforced thermoplastic composites: Current understanding and challenges," *Compos. Part A Appl. Sci. Manuf.*, vol. 149, p. 106578, 2021, doi: 10.1016/j.compositesa.2021.106578.

[3] B.H.A.H. Tijs, A. Turon, and C. Bisagni, "Characterization and analysis of conduction welded thermoplastic composite joints considering the influence of manufacturing," *Compos. Struct.*, vol. 348, p. 118505, 2024, doi: 10.1016/j.compstruct.2024.118505.

[4] P.P. Parlevliet, H.E.N. Bersee, and A. Beukers, "Residual stresses in thermoplastic composites – A study of the literature – Part I: Formation of residual stresses," *Compos. Part A Appl. Sci. Manuf.*, vol. 37, no. 11, pp. 1847–1857, 2006, doi: 10.1016/j.compositesa.2005.12.025.

[5] I.F. Villegas and P. Vizcaino Rubio, "On avoiding thermal degradation during welding of high-performance thermoplastic composites to thermoset composites," *Compos. Part A Appl. Sci. Manuf.*, vol. 77, pp. 172–180, 2015, doi: 10.1016/j.compositesa.2015.07.002.

[6] K. Minchenkov, S. Gusev, I. Sergeichev, and A. Safonov, "Improving the thermal performance of PVC windows with pultruded thermoplastic reinforcement," *Sci. Rep.*, vol. 15, p. 1996, 2025, doi: 10.1038/s41598-025-86019-6.

[7] M. Kozielczyk, K. Mencel, J. Kowalczyk, and M. Paczkowska, "Selection of processing methods and parameters for composite inserts in window profiles with regard to the strength of their welds," *Materials*, vol. 18, no. 1, p. 44, 2025, doi: 10.3390/ma18010044.

[8] V.K. Stokes, "Hot-tool and vibration welding of poly(vinyl chloride)," *J. Vinyl Addit. Technol.*, vol. 6, no. 3, pp. 158–165, 2000, doi: 10.1002/vnl.10245.

[9] C.J. Nonhof, "Optimization of hot plate welding for series and mass production," *Polym. Eng. Sci.*, vol. 36, no. 9, pp. 1184–1195, 1996, doi: 10.1002/pen.10512.

[10] H. Potente and J. Schnieders, "Influence of process parameters on the phenomenon of stress cracking during hot plate welding," *J. Reinf. Plast. Compos.*, vol. 21, no. 6, pp. 489–496, 2002, doi: 10.1177/0731684402021006828.

[11] M.J. Oliveira, C.A. Bernardo, and D.A. Hemsley, "Morphology and mechanical behavior of polypropylene hot plate welds," *Polym. Eng. Sci.*, vol. 41, no. 11, pp. 1913–1922, 2001, doi: 10.1002/pen.10888.

[12] S.-J. Liu and H.-F. Cheng, "The influence of interface geometry on the joint strengths of hot plate welded composites," *J. Reinf. Plast. Compos.*, vol. 29, no. 4, pp. 497–509, 2010, doi: 10.1177/0731684408099410.

[13] W.H. Starnes Jr., "Structural and mechanistic aspects of the thermal degradation of poly(vinyl chloride)," *Prog. Polym. Sci.*, vol. 27, no. 10, pp. 2133–2170, 2002, doi: 10.1016/S0079-6700(02)00063-1.

[14] M. Beltrán and A. Marcilla, "Fourier transform infrared spectroscopy applied to the study of PVC decomposition," *Eur. Polym. J.*, vol. 33, no. 7, pp. 1135–1142, 1997, doi: 10.1016/S0014-3057(97)00001-3.

[15] J. Yu, L. Sun, C. Ma, Y. Qiao, and H. Yao, "Thermal degradation of PVC: a review," *Waste Manag.*, vol. 48, pp. 300–314, 2016, doi: 10.1016/j.wasman.2015.11.041.

[16] Z. Hadj Amar, S.F. Chabira, and M. Sebaa, "Thermal aging effects on the microstructure of rigid PVC tubes used for water transportation in sub-Saharan region," *Mater. Today Proc.*, vol. 49, no. 4, pp. 1035–1040, 2022, doi: 10.1016/j.matpr.2021.09.025.

[17] M. Saad *et al.*, "The impact of heat and humidity on unplasticized poly(vinyl chloride)," *Polym. Degrad. Stab.*, vol. 238, p. 111334, 2025, doi: 10.1016/j.polymdegradstab.2025.111334.

[18] P. Postawa, T. Stachowiak, and A. Gnatowski, "Strength analysis of welded corners of PVC window profiles," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 225, no. 1, p. 012003, 2017, doi: 10.1088/1757-899X/225/1/012003.

[19] M. Wygoda, M. Paprocki, and W. Adamczyk, "Influence of the welding process on the quality of PVC frames," *Manuf. Technol.*, vol. 22, no. 3, pp. 356–366, 2022, doi: 10.21062/mft.2022.037.

[20] M. Kozielczyk, K. Mencel, J. Kowalczyk, and M. Paczkowska, "Analysis of the strength and quality properties of welded PVC profiles with glass fiber composite reinforcement in the context of milling and weld head feed," *Materials*, vol. 18, no. 6, p. 1297, 2025, doi: 10.3390/ma18061297.

[21] M. Kozielczyk, J. Kowalczyk, and M. Paczkowska, "Analysis of the effects of weld melt duration on joint integrity and surface quality during profile milling," *Appl. Sci.*, vol. 15, no. 20, p. 11024, 2025, doi: 10.3390/app152011024.

[22] M. Kozielczyk, J. Kowalczyk, and M. Paczkowska, "The influence of welding temperature on the durability and quality of composite-reinforced window profile joints," *Inż. Bud.*, no. 3, pp. 349–353, 2026, doi: 10.5604/01.3001.0055.7424.