Impregnation and Bonding of Hybrid Wood-Based Materials in Automotive Body Shell

Moira Burnett,[a] Nina Ritter,[a] Dirk Berthold,[a] Jannis Heise,[b] Nils Ratsch,[b] and Martin Kahlmeyer [b]

*Corresponding author: moira.burnett-barking@wki.fraunhofer.de

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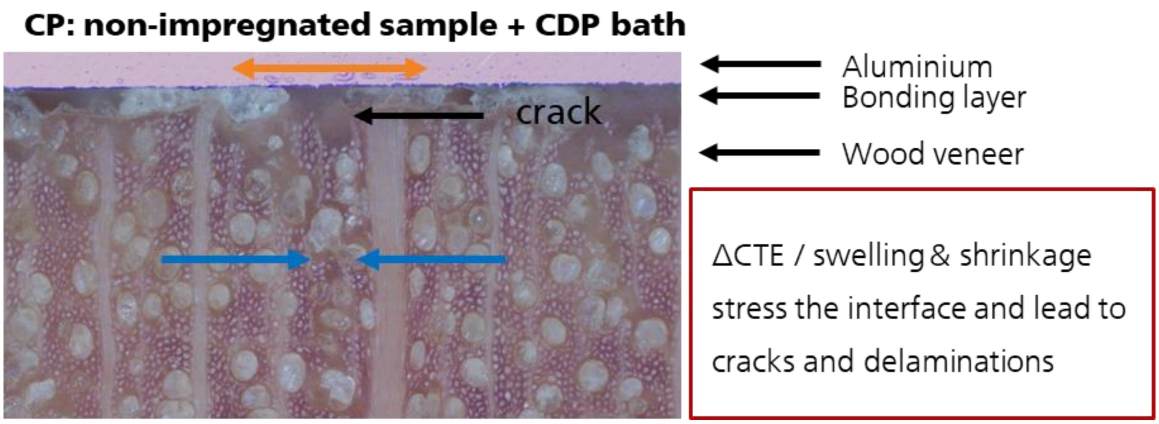
GRAPHICAL ABSTRACT



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The behaviour of wood-metal composites was evaluated during cathodic dip coating, which is a standard corrosion protection process for metals in automotive engineering. In this process, the materials are exposed to chemical and thermal stresses, which is a challenge for wood and composites based thereon, especially in terms of the durability of the adhesive and the differences in thermal expansion. In this study, a hydrophobic surface sealant was proposed to mitigate these negative effects by reducing moisture absorption during dipping baths. The mechanical properties, including flexural strength, tensile strength and impact strength of aluminium-plywood composites were evaluated. It was found that impregnation with low-viscosity resins improved the mechanical properties by increasing the bulk density of the wood. Although the dip coating process reduced the strength of the impregnated samples, they maintained higher values compared to the non-impregnated samples. The dip coating process significantly reduced the tensile strength of the non-impregnated samples, while the impregnation protected the samples and maintained the tensile strength. It was concluded that hydrophobic surface sealing by impregnation is crucial for improving the mechanical properties of wood composites in automotive applications, as it reduces moisture absorption and maintains mechanical integrity during the dip coating process.

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Keywords: Hybrid wood composites; Plywood; Impregnation; Automotive body shell; Cathodic dip coating; Swelling; Coefficient of thermal expansion

Contact information: a: Technology for Wood and Natural Fiber-based Materials, Fraunhofer Institute for Wood Research, Riedenkamp 3, 38108 Braunschweig, Germany; b: Department for Cutting and Joining Technologies (tff), University of Kassel, Kurt-Wolters-Straße 3, 34125 Kassel;
** Corresponding author: moira.burnett-barking@wki.fraunhofer.de*

INTRODUCTION

In the recent past, the potential of wood or hybrid wood composites has been rediscovered and several publicly funded research projects involving automotive OEMs have already been carried out, such as HAMMER and For(s)tschritt (BMBF/BMEL) in Germany or WoodC.A.R and CARpenTIER (FFG) in Austria. The general approach in these projects is to combine and enhance materials and their properties to create a sustainable composite that fulfils even the high requirements of the automotive body shell (Henning *et al*. 2011). In the HAMMER project (BMBF/VDI), for example, beech plywood was bonded with various materials, primarily metal, in order to increase the specific stiffness and thus improve its suitability for automotive structures. In the end, the wood-based material met the basic requirements of the automotive industry and a followup project For(s)tschritt (BMWK/TÜV) was launched. This project concentrated on the development of formed plywood for structural applications in automotive and railway contexts. The primary objective was to leverage the advantages of metal-wood composites for large-area structural assemblies, achieving substantial mass reductions while maintaining minimal environmental impact in vehicle applications. Investigations encompassed the design and mechanical properties of these composites, as well as their fundamental suitability for cathodic dip coating (CDP) processes. As a result of the project, a semi-structural component, specifically a side door bumper, was successfully developed as a demonstrator. This component consisted of a laminated composite based on beech veneer reinforced with a metal strip on one side. The unidirectional metal reinforcement was designed to absorb energy in the event of a collision, highlighting its potential for crash-resilient applications in transportation structures (Kohl *et al.* 2016, 2017; Käse *et al.* 2019; Große *et al.* 2020). The Austrian projects Wood C.A.R. (FFG) and CARpenTIER (FFG) are also investigating wood as a structural component in the automotive industry through virtual engineering, material behaviour analysis and cross-innovation for production and recycling (Jost *et al.* 2018). In all these projects and studies, the physical-mechanical properties of hybrid wood-based materials were demonstrated for the mobile sector.

The cathodic dip coating process (CDP) is the state of technology in the automotive industry to protect metals against corrosion by applying a high-quality coating on the entire electrically conductive surface (Fig. 1). The first step in this process is phosphatisation, in which the car body is alkaline degreased (pH >10 to 11), rinsed with demineralised water, immersed in an activation solution, treated with the phosphoric acid trication phosphating solution, and finally rinsed again with demineralised water. In the subsequent CDP bath, the body is exposed to pigments, binder, water, and acid, where the CDP layer is finally deposited by an electrochemical process. In order to bake the coating, the components are driven into an oven and heated to >160 °C. Almost all body-in-white components (structural elements of a vehicle's body shell before painting and assembly) pass through these lines and are therefore exposed to the described influences. In recent years, low-energy powder coatings have been introduced, which can be cured at temperatures as low as 160 °C. Significant efforts are currently being directed towards both reducing curing temperatures and optimising the utilisation of thermal energy within the process (Scheffels 2018). However, other studies emphasise the need to reduce curing temperatures to 125 °C, especially in view of the increasing integration of materials such as plastics and (natural) fibre-reinforced composites (FRP), including thermoplastic and thermoset variants (Axalta Coating Systems Germany 2018). The desire for low-bake coating systems with lower drying temperatures (120 °C) is therefore obvious, but such systems will not be able to completely replace established processes with high curing temperatures in the near future. Therefore, for advanced hybrid wood-metal composites (WMC), it is necessary to understand the behaviour of these materials in the CDP (Scheffels 2018).

Hybrid materials pose a challenge. Adhesives can be washed out if not sufficiently cured, and high stresses can occur due to different thermal expansions of the materials (ΔCTE). In case of wood-based hybrid materials particular challenges arise, as the open-pored and hydrophilic wood-structure is known to cause swelling at high moisture levels. In addition, in the CDP wood is exposed to a complex temperature profile in which the heat repeatedly rises above 100 °C (Fig. 1).

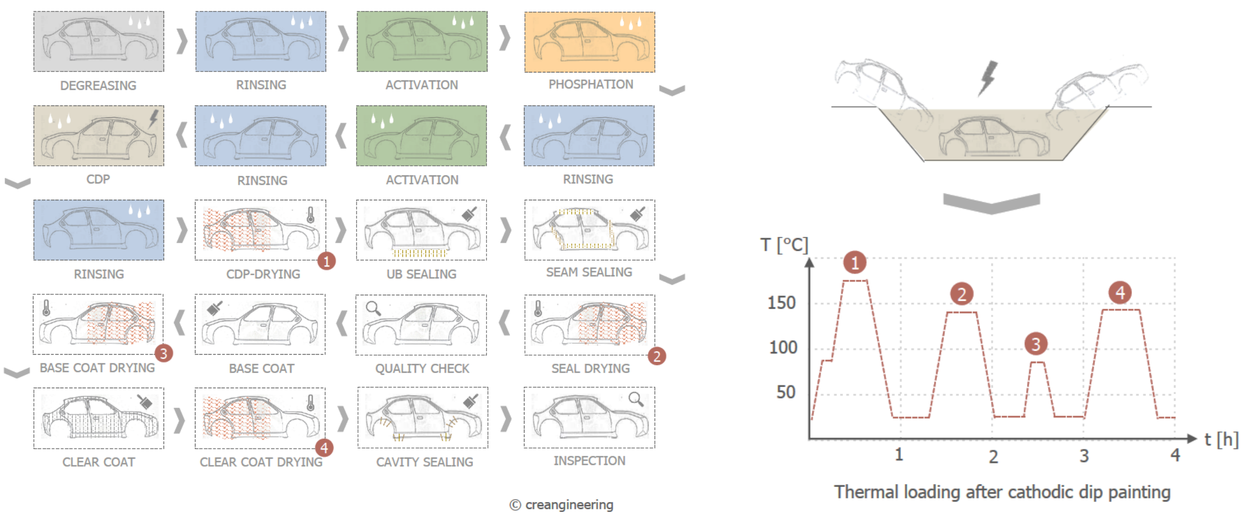

Fig. 1. Painting process in car body construction (left) with temperature profile as an example (right) (© creangineering)

Besides the possible damage of lignin and hemicellulose caused by thermal degradation at high temperatures (Haiping *et al.* 2007), these phases lead to the evaporation of water and thus to shrinkage. The ΔCTE behaviour known from other material combinations also occurs in WMC and leads to anisotropic relative displacements between substrates and adhesive. However, this effect is superimposed by the change in shape due to different moistures: When the temperature increases, the thermal expansion of metal and adhesive is affected by the sudden shrinkage of the initially moist wood, leading to large displacements and high stresses. When cooling down and in a humid environment, the situation is reversed and leads to opposing stresses, particularly in the joint zone of the WMC.

The proven suitability of wood-metal composites (WMC) for structural applications in vehicle construction (Petersen and Solberg 2005; Leskinen *et al.* 2018; Mair-Bauernfeind *et al.* 2020) underscores their potential for use in car body construction such as door side bumper. However, their integration in the body shell requires resilience to the cathodic dip coating process. Therefore, this study examined the impact of the CDP on WMC and evaluated the effectiveness of a simple hydrophobic surface sealant for wood in mitigating adverse effects, such as moisture absorption in the immersion baths. In the context of the For(s)tschritt project, panel composites with a high wood content, coated with metal on one side, were investigated.

EXPERIMENTAL

Composite Manufacturing

A hybrid composite material was fabricated using 5-layer beech plywood with an aluminum sheet applied to one side. This configuration contrasts with a closed sandwich, where aluminum is placed on both sides of the wood, preventing direct contact between the cathodic dip coating (CDP) and the wood. The materials were bonded using polyurethane (PUR-A, PUR-B) or emulsion polymers (EPI) with an application weight of 200 g/m². Initially, plywood was obtained by combining 5 veneer layers with a layer orientation of 0°/90°. The veneer layers were placed in a hot press and compacted (temperature: 120 °C, pressure: 1 N/mm², pressing time: 8 min) before the aluminium sheet was laminated on (temperature: 80 °C, pressure: 1 N/mm², pressing time: 5 min). Subsequently, the samples were milled into the geometry to determine flexural strength (MOR), tensile strength (TS), and impact strength (IB). To investigate the influence of hydrophobisation, half of the samples were impregnated in a vacuum chamber with a water-based dispersion containing isocyanate (PUR; viscosity 70 mPas). Density values of the non-impregnated and impregnated samples were 0.92 g/cm³ and 1.1 g/cm³.

After a curing and conditioning phase (20 °C at 65 % RH) of 10 days, samples were subjected to a laboratory CDP, consisting of a stainless steel tank with internal dimensions of 450 x 450 x 300 mm³, in which a stainless steel immersion heater with 1500 W (Rommelsbacher TS 1502) was applied. A universal temperature switch (H-Tronic UTS 125) was used to regulate the temperature to 55 ± 0.1 °C, while constant circulation and uniform heating was ensured by an immersion pump with a maximum flow rate of 300 L/min. A commercial zinc phosphating bath was used as CDP liquid. One set of impregnated and not impregnated samples was treated in a manner typically used for the CDP with the following steps: 1: Bath for 10 min; 2. Oven drying at 180 °C; 3: Bath for 10 min; 4: Oven drying. After CDP, the samples were conditioned for 5 days (20 °C at 65 % RH) and then tested for their mechanical properties (Fig. 2).

Table 1. Overview of Test Parameters

Factor	Parameter
WMC	Wood: 5 layered beech plywood (Thickness: 1.5 mm) Metal: Aluminium alloy (Thickness: 1.2 mm)
Adhesive for bonding the WMC	1-C Polyurethane (PUR A and PUR B; Jowat, Germany) Emulsion-Polymer-Isocyanat (EPI; Jowat, Germany)
Impregnation	50 % of samples were impregnated in a vacuum chamber with an 1-C moisture curing polyurethane to increase water resistance (Jowat, Germany)
Emulsion for CDP	Zinc-phosphate immersion bath (Chemetall, Langelsheim)
Variants	Ref: no impregnation + no CDP CDP: no impregnation + CDP I: impregnation + no CDP I-CDP: impregnation + CDP
Testing	Bending strength (EN 310) Tensile strength (DIN 52377) Impact bending strength (ISO 179-1)

The MOR was investigated using a three-point bending test according to EN 310 (1993). Three panels were produced for each variant, so that at least 8 identical samples (150 x 50 mm²) could be obtained. The applied force was aligned on the wood surface, perpendicular to the wood fibre using a universal testing machine (Zwick Roell Z100) at a constant test speed of 10 mm/sec. The values given are mean values of the individual test series.

The TS was determined according to DIN 52377 (2016). For each variant, three panels were produced to gain at least 3 identical specimens per parameter (230 x 40 mm²), and these were loaded at a constant test speed of 10 mm/sec until failure.

The IB was tested according to ISO 179-1 (2023) with a laboratory pendulum impact tester with a maximum energy of 50 J (Zwick Roell). The impact test was carried out on 15 x 8 x 110 mm³ samples (flatwise impact), perpendicular to the fibre direction, with a span of 68 mm. For each variant, 9 samples were tested.

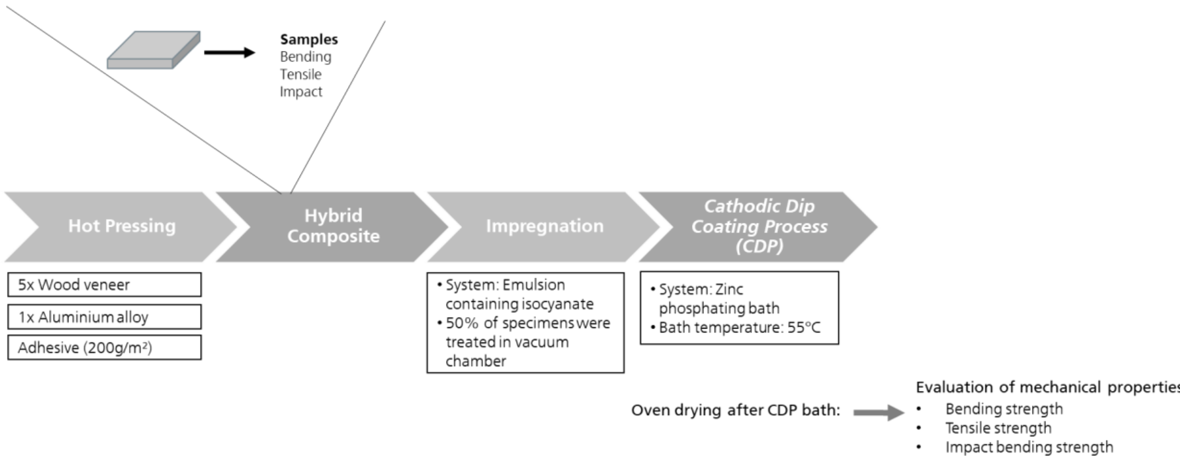

Fig. 2. Overview experimental setup

RESULTS AND DISCUSSION

Mechanical Properties

Bending strength

Figure 3 illustrates the significant influence of the adhesive on the mechanical strength properties of the WMC. Variants bonded with EPI exhibited the lowest strength values, regardless of impregnation (either reference or impregnated) or exposure to CDP process. No significant differences in strength were observed between the variants bonded with PUR A or PUR B, respectively. However, a decrease in MOR was observed for both PUR adhesives after a CDP (PUR A CDP 13%; PUR B CDP: 10%). The test results indicate that impregnation had a positive influence on the MOR. This process led to an increase in bulk density, which consequently enhanced the MOR. Specifically, the impregnated variant bonded with PUR B demonstrated a 47% increase in strength compared to the non-impregnated reference samples (PUR B: Ref vs. I). Although the MOR of impregnated samples was generally reduced by the CDP process, a high strength value of 2.1 kN was still achieved (PUR B: I-CDP).

The observed significant decrease in the MOR following CDP treatment can be attributed to the elevated temperatures ranging from 150 to 180 °C. Such high temperatures provoke ΔCTE-stresses within the hybrid composite, particularly between the metal (α = 23.0 × 10^{-6} m/(m·K)) and the wood (α = 3.3 × 10^{-6} m/(m·K)) (Niemz and Sonderegger 1993). Furthermore, the hydrophilic nature of the wood contributes to the observed composite's behaviour. During the CDP bath, the semi-ring porous wood with vessels (pores) and wooden rays absorbs moisture, which is subsequently released during the drying process in the oven. This absorption and release of moisture result in swelling and shrinkage movements within the wood, generating internal stresses that influence the integrity of the bond within the composite (Fig. 4).

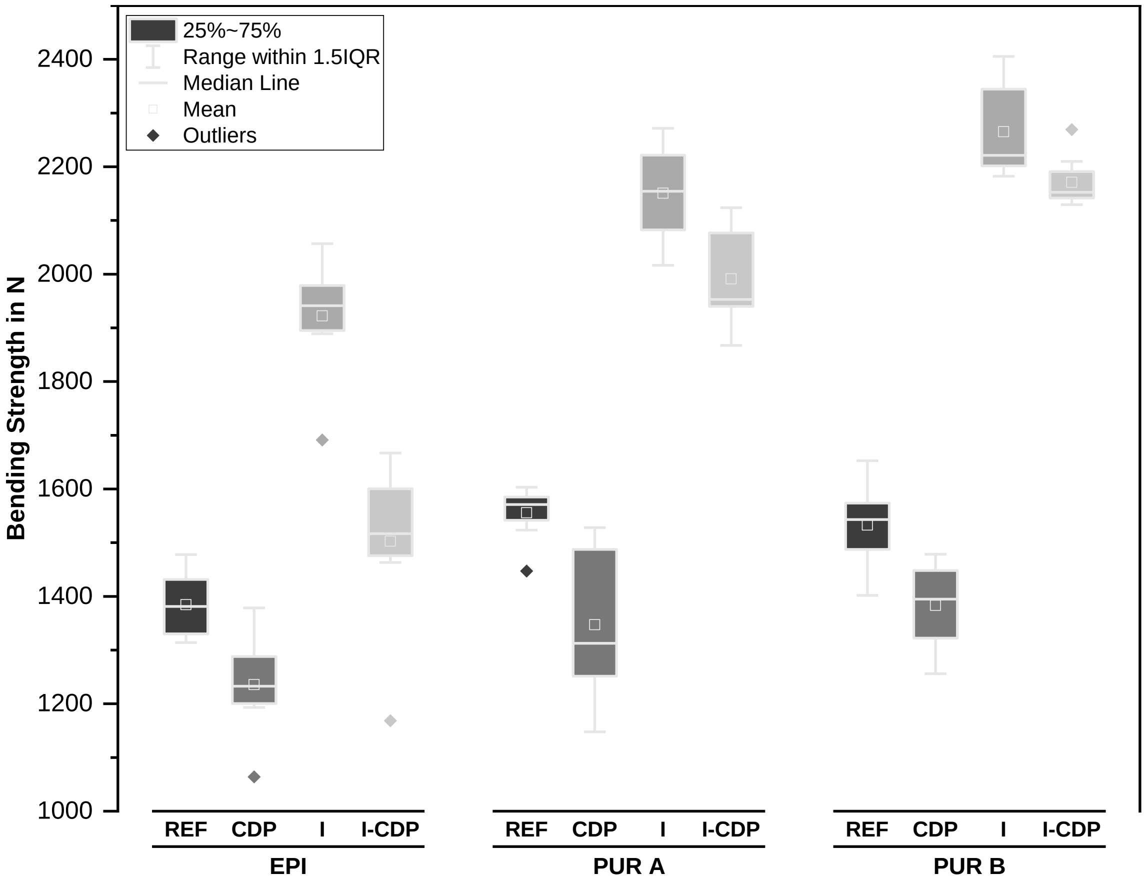

Fig. 3. Influence of Impregnation and CDP on MOR of WMC; Adhesives: EPI, PUR A, PUR B; Variants: Ref: reference, CDP: cathodic dip coating process, I: Impregnation, I-CDP: Impregnation+ cathodic dip coating process

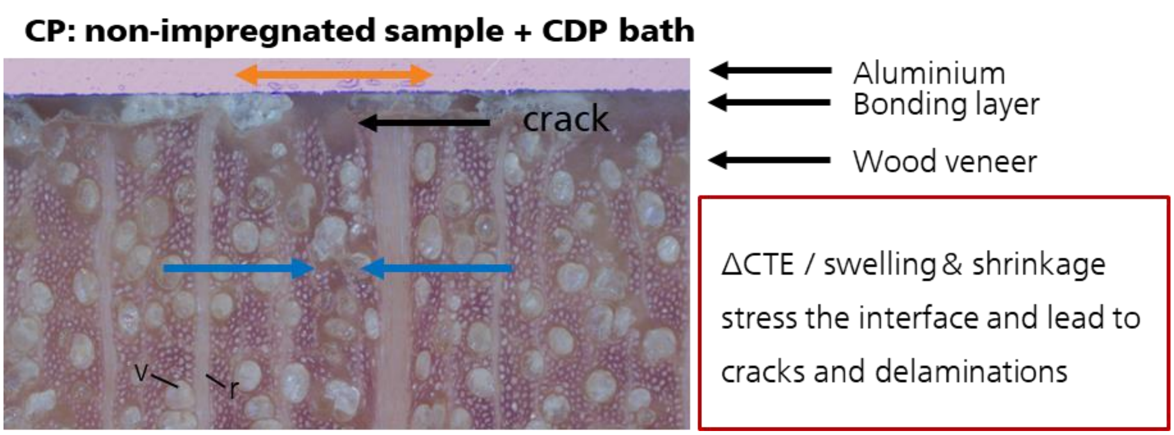

Fig. 4. Cross section of a sample PUR A-CDP: not impregnated + CDP; extension of metal layer (red arrow) and shrinkage of wood material (blue arrow) due to high temperature in the drying phase; wood structure: v: vessel, r: wooden ray

Tensile strength

Figure 5 illustrates the achieved TS values at the point of wood failure. It is apparent that EPI was less effective for bonding WMC compared to PUR. The CDP treatment notably exerted a strong negative impact on non-impregnated samples, leading to a significant reduction in TS. In the course of post-treatment, partial delamination of the bond occurred, resulting in a TS decrease of approximately 19% compared to the reference (EPI Ref vs. EPI CDP) (Fig. 5). Additionally, the results suggest that impregnation did not enhance the strength of EPI-bonded composites; however, it mitigated the drop in strength after CDP treatment. Consistent with the results observed for MOR, the PUR-bonded composite panels exhibited markedly superior strength properties after impregnation. The strength increased by 28% and 10% (PUR A: I; PUR B: I) following impregnation treatment with a low-viscosity resin. Furthermore, the process stabilised the composite so that surface was sealed and negative effects caused by CDP treatment were effectively prevented.

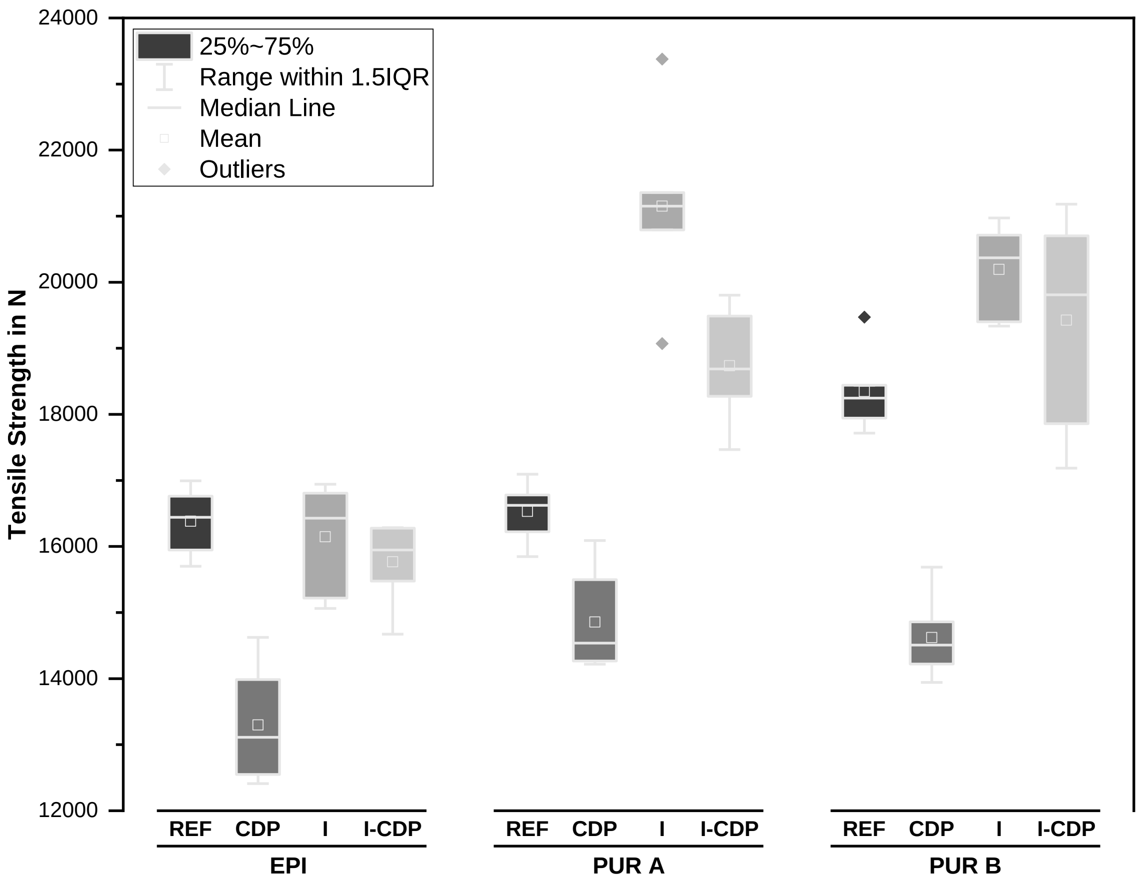

Fig. 5. Influence of Impregnation and cathodic dip coating process on TS of WMC; Adhesives: EPI, PUR A, PUR B; Variants: Ref: reference, CDP: no impregnation + cathodic dip coating process, I: Impregnation, I-CDP: Impregnation + cathodic dip coating process

Impact bending strength

Figure 6 indicates that neither the CDP treatment nor impregnation had a significant effect on the IB strength of the composites. The primary factor influencing IB strength was the adhesive system (EPI or PUR). Specifically, composites bonded with EPI exhibited lower IB strength compared to those bonded with PUR, although no significant differences were observed between the EPI or PUR variants for a given adhesive (EPI: Ref vs EPI: I+CDP). However, an examination of the fracture patterns revealed that impregnation influenced the fracture behaviour, leading to brittle failure where the samples simply crack (Fig. 7). In contrast, non-impregnated samples demonstrated greater flexibility and did not exhibit brittle fracture. This brittleness may pose a drawback for applications in the body shop, where energy absorption is crucial.

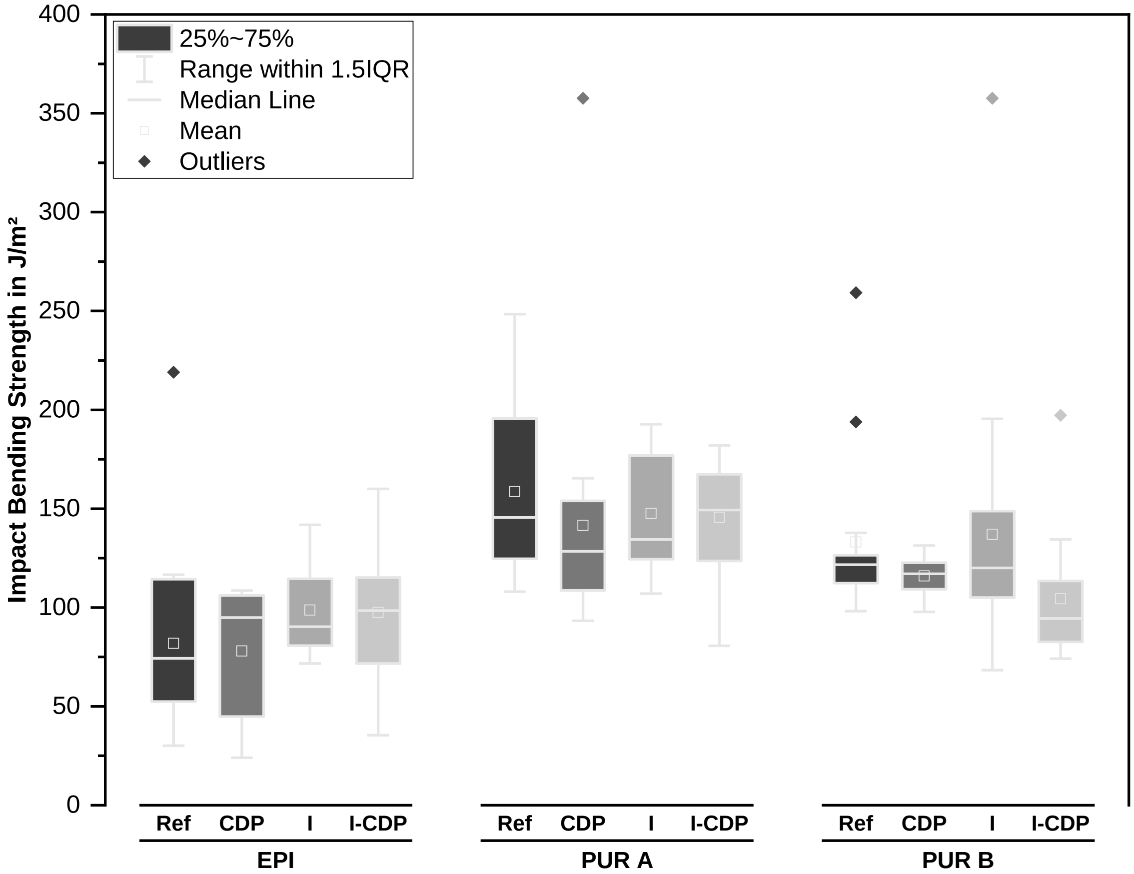

Fig. 6. Influence of Impregnation and cathodic dip coating process on IB of WMC; Adhesives: EPI, PUR A, PUR B; Variants: Ref: reference, CDP: cathodic dip coating process, I: Impregnation, I-CDP: Impregnation+ cathodic dip coating process

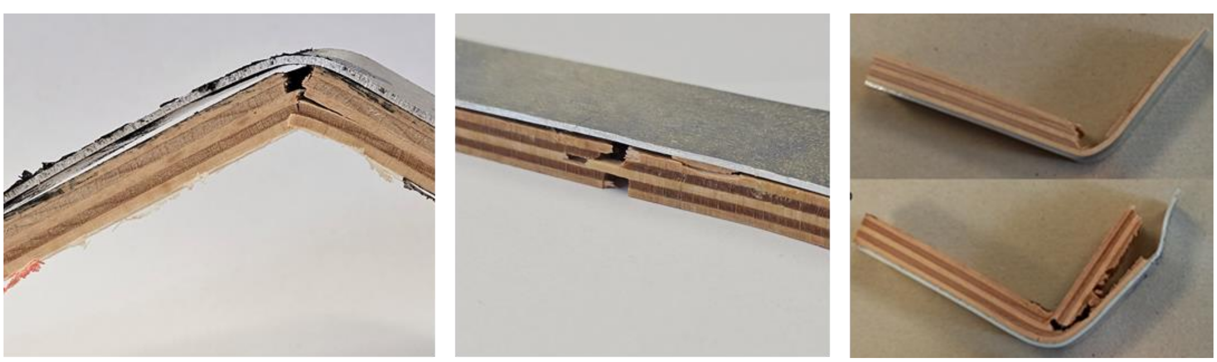

Fig. 7. Failure mode after testing; left: Bending strength; middle: Tensile strength; right: Impact bending strength

CONCLUSIONS AND OUTLOOK

If wood-based materials are to be used in the car body, they must be adapted to the manufacturing process and be able to pass through it. In the case of the body shell, this means that the hybrid wood-based materials will go through the cathodic dip process (CDP). The present study has shown this:

1. CDP is a major challenge and negatively affects untreated wood elements. If a wood-metal composite (WMC) is put into the CDP without additional protection of the wood structure, then these elements will be damaged and their strength properties will be reduced dramatically, regardless the adhesive system (EPI or PUR).
2. The application of a surface impregnation with low-viscosity resin improves the strength enormously and reduces the effects of CDP. Impregnation is therefore one way of making the WMC suitable for body shell. However, the lightweight potential of wood is maintained compared to other materials, as only the near surface layer is impregnated and not the entire wood composite.

The next part of the study will focus on isolating the distinct contributions of thermal, chemical, and humidity-related factors to enhance the understanding of their individual effects. Experimental investigations will encompass sandwich structures composed of aluminum on both sides, enabling comparisons with configurations featuring aluminum on a single side. Furthermore, an expanded range of wood-based materials will be examined to evaluate the generalizability of the findings. Long-term durability assessments will be conducted to analyse material performance under diverse environmental conditions. In parallel, mathematical models will be developed to predict material behaviour, incorporating variables such as temperature, humidity, and thermal expansion, including the impact of sandwich structure.

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