

## RECYCLING OF POLYURETHANE MACHINING CHIPS INTO CARBON/EPOXY SANDWICH COMPOSITES

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### Abstract

Polyurethane (PU) modelling boards and foams are widely used for manufacturing prototypes, models, and moulds; however, CNC machining generates substantial amounts of fine chips and dust that are typically downcycled or landfilled. This paper presents a mechanically straightforward upcycling route in which PU machining chips are milled, sieved, and re-used as a loose particulate core in carbon/epoxy sandwich composites. The sandwich panels were manufactured by hand lay-up with vacuum assistance or by vacuum infusion to keep the process low-tech and readily transferable to prototyping practice. Flexural behaviour was assessed by three-point bending in accordance with ISO 178, and the results were interpreted using load–deflection responses complemented by macroscopic inspection and fractographic evaluation of failed specimens. A characteristic sandwich response was observed, with damage initiation in the core (shear and local densification) followed by a transfer of load being carried predominantly by the facesheets. The discussion shows that mechanical stability is particularly sensitive to the homogeneity of the particulate layer, local porosity, and the degree of matrix infiltration, which together govern the core shear capacity and the adhesion at the facesheet–core interface. The proposed approach demonstrates the material potential of recycled PU chips for lightweight composite panels and identifies key optimisation directions to improve process repeatability and scalability in model and mould manufacturing. The concept leverages the fact that the flexural stiffness and strength of a sandwich are primarily determined by the facesheets, whereas the core provides shear transfer and stabilisation. Overall, the study contributes to circular-economy strategies for modelling materials and highlights practical pathways for value-added utilisation of waste PU fractions.

**Keywords:** polyurethane recycling, CNC machining waste, sandwich composite, carbon fibre, mechanical testing

### 1. INTRODUCTION

Polyurethanes (PU) constitute a versatile class of polymers used in rigid and flexible foams, elastomers, and modelling boards for prototyping. In addition to end-of-life waste, a non-negligible waste stream is generated already during manufacturing and machining, where fine chips and dust are produced. Compared with chemical recycling, mechanical processing (grinding) followed by reuse represents one of the most accessible routes for industrial implementation; however, it often results in low-value applications [1]. Current research therefore focuses on incorporating mechanically recycled PU fractions into new composite materials in order to preserve higher functional value, for example as fillers in polymer composites within the framework of the circular economy [2, 3, 4]. Sandwich structures combining stiff fibre-reinforced face sheets with a lightweight core are particularly attractive for such upcycling because their performance is governed by the synergy between the face sheets and the core rather than solely by the absolute properties of the core material [5, 6, 7]. In the present study, PU chips generated during machining are utilised as a particulate core layer in a carbon/epoxy sandwich laminate. The aim is (i) to demonstrate manufacturability using a low-

cost hand lay-up process with vacuum assistance and (ii) to quantify the flexural behaviour of the resulting sandwich beams as an initial indicator of load-transfer capability and damage mechanisms.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The source PU material was a rigid polyurethane modelling board RAKU TOOL SB-0140 (**Figure 1**) [8]. Carbon fabrics with areal weights of  $245 \text{ g}\cdot\text{m}^{-2}$  (2/2 twill, outer layer) and  $600 \text{ g}\cdot\text{m}^{-2}$  (load-bearing backing layers) were used as reinforcement. The matrix consisted of a two-component epoxy system (LH 160 resin with H 505 hardener) mixed at a weight ratio of 100:27 in accordance with the supplier's recommendation [9]. Demoulding was ensured using a wax-based release agent and a PVA-based release film.

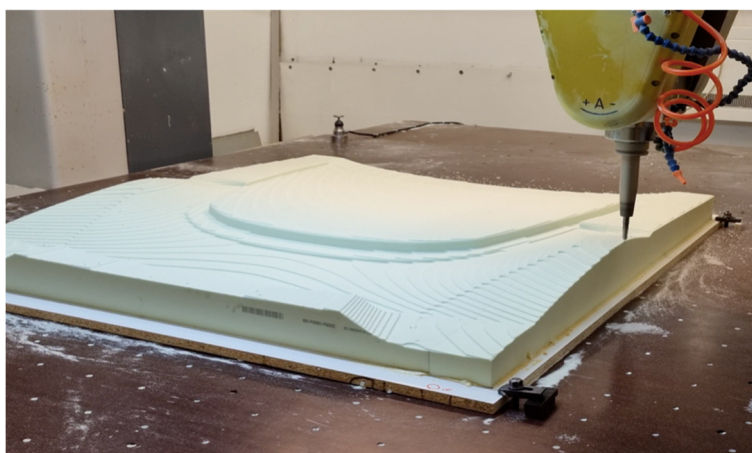


**Figure 1** CNC machining of the PU modelling board

### 2.2 Preparation of the recycled PU chip core

PU chips were generated during CNC machining of the modelling board. The collected chips/dust were subsequently subjected to further mechanical size reduction (grinding) to obtain a particulate fraction suitable for handling and lay-up (**Figure 2**). No chemical treatment was applied; the procedure therefore represents a purely mechanical recycling step.



**Figure 2** Chips generated during machining of the PU modelling board

### 2.3 Manufacturing of the sandwich composite

Pilot sandwich panels were manufactured on a flat mould using a hand lay-up process with vacuum assistance. The face sheets consisted of carbon fabric layers, while a layer of recycled PU chips was inserted between the face sheets as the core (**Figure 3**). The nominal stacking sequence was CF245/CF600/CF600 / PU chips / CF600/CF245 (from bottom to top), **Table 1**. After lay-up, the assembly was vacuum-bagged, and a 2 mm thick aluminium cover plate was applied to promote thickness uniformity and surface quality. The laminate was cured at laboratory temperature for 24 h and then demoulded. Test specimens were cut using a diamond saw. The density of the manufactured sandwich composite was  $1065 \text{ kg}\cdot\text{m}^{-3}$ , as determined from the specimen mass and geometric volume.



**Figure 3** Schematic of the sandwich structure with a recycled PU chip core between carbon/epoxy face sheets

**Table 1** Materials used in the pilot sandwich composite

| Component                          | Designation                                   | Function                       | Notes                                                     |
|------------------------------------|-----------------------------------------------|--------------------------------|-----------------------------------------------------------|
| PU source material                 | RAKU TOOL SB-0140                             | Precursor of the recycled core | Waste generated during CNC machining; mechanically ground |
| Carbon fabric (outer layer)        | $245 \text{ g}\cdot\text{m}^{-2}$ , twill 2/2 | Outer face-sheet layer         | Improved surface quality                                  |
| Carbon fabric (load-bearing layer) | $600 \text{ g}\cdot\text{m}^{-2}$             | Load-bearing face-sheet layer  | Load-bearing layers responsible for load transfer         |
| Epoxy matrix                       | LH 160 + H 505 (100:26)                       | Matrix/binder                  | Cured at laboratory temperature                           |

### 2.4 Flexural test

The flexural properties were determined by a three-point bending test in accordance with ISO 178. [10] Seven specimens ( $n = 7$ ) with dimensions of  $140 \times 10 \times 7 \text{ mm}$  were tested. The support span was 112 mm and the crosshead speed was  $2 \text{ mm}\cdot\text{min}^{-1}$ . The applied load and mid-span deflection were recorded, and the flexural stress was calculated as  $\sigma_f = 3FL / (2bh^2)$ , where  $F$  is the applied load,  $L$  is the support span, and  $b$  and  $h$  are the specimen width and thickness, respectively. The density of the manufactured sandwich composite was  $1065 \text{ kg}\cdot\text{m}^{-3}$ . Representative stress–deflection curves for all seven specimens are shown in **Figure 3**. A pronounced scatter was observed, with the maximum flexural stress ranging from 52 to 132 MPa (**Table 2**). The best-performing specimen (VAC\_Forma\_3) reached 132 MPa, whereas the lowest value recorded for VAC\_Forma\_4 was approximately 52 MPa. The curves typically exhibit an initial quasi-linear region followed by a more compliant response, which is consistent with early core damage (shear/crushing) and the progressive mobilisation of the face sheets.

### 3. RESULTS

#### 3.1 Flexural response

The density of the manufactured sandwich composite was  $1065 \text{ kg}\cdot\text{m}^{-3}$ . Representative stress–deflection curves for all seven specimens are shown in **Figure 4**. A pronounced scatter was observed, with the maximum flexural stress ranging from 52 to 132 MPa (**Table 2**). The best-performing specimen (VAC\_Forma\_3) reached 132 MPa, whereas the lowest value recorded for VAC\_Forma\_4 was approximately 52 MPa. The curves typically exhibit an initial quasi-linear region followed by a more compliant response, which is consistent with early core damage (shear/crushing) and the progressive mobilisation of the face sheets.

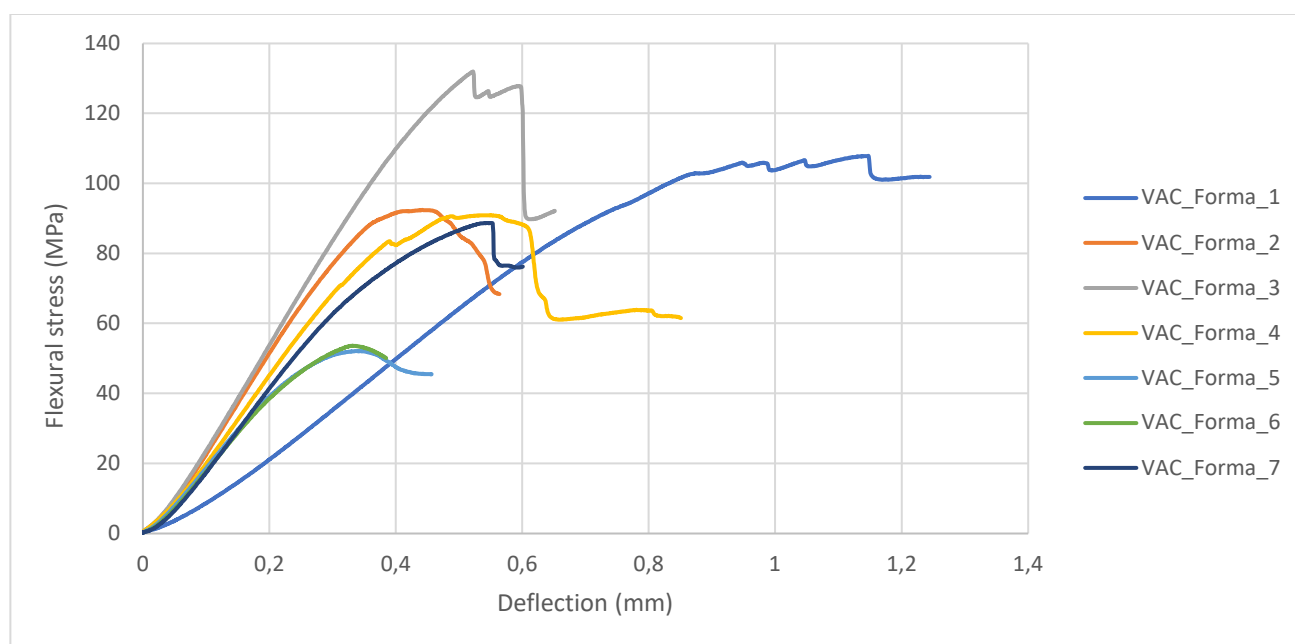


**Figure 4** Flexural stress–deflection curves for sandwich beams with a recycled PU core

**Table 2** Maximum flexural values for the individual specimens

| Specimen         | Flexural stress (MPa) | Deflection (mm)      |
|------------------|-----------------------|----------------------|
| VAC_Forma_1      | 107.9                 | 1.244                |
| VAC_Forma_2      | 92.4                  | 0.564                |
| VAC_Forma_3      | 131.9                 | 0.651                |
| VAC_Forma_4      | 90.9                  | 0.851                |
| VAC_Forma_5      | 52.2                  | 0.456                |
| VAC_Forma_6      | 53.6                  | 0.385                |
| VAC_Forma_7      | 88.7                  | 0.601                |
| <b>Mean ± SD</b> | <b>88.2 ± 28.3</b>    | <b>0.679 ± 0.290</b> |

#### 3.2 Failure modes

Macroscopic post-flexural inspection revealed combined failure modes involving face-sheet cracking and local face sheet/core debonding. In several specimens, the recycled PU core exhibited local crushing and shear band formation in the mid-span region, whereas the carbon/epoxy face sheets showed tensile

cracking on the lower surface. **Figure 5** presents a representative failed specimen with clearly visible damage localisation within the core region.



**Figure 5** Typical post-test condition of the specimen indicating core damage and face-sheet cracking

#### 4. DISCUSSION

The pilot results confirm that mechanically recycled PU chips can function as a lightweight core layer capable of transferring shear between stiff carbon/epoxy face sheets, which is the key role of the core in sandwich bending [7]. However, the large scatter observed (coefficient of variation of approximately 32% for the maximum flexural stress) indicates pronounced sensitivity to both processing conditions and material heterogeneity. Unlike conventional foam cores, the particulate PU layer is inherently heterogeneous, and its load-bearing capacity depends on particle arrangement, local porosity, the extent of epoxy infiltration, and the degree of mechanical interlocking at the face sheet/core interface. Similar conclusions have been reported for composites containing mechanically recycled PU fractions, where microstructural non-uniformity and weak interfaces limit the repeatability of mechanical performance [2, 3, 4]. The best-performing specimens most likely benefited from more uniform core compaction and improved resin wet-out, which delayed core shear failure and allowed the face sheets to sustain higher flexural stresses. Conversely, premature core crushing or interfacial debonding may reduce effective shear transfer and initiate early face-sheet cracking, thereby resulting in lower peak values. From a sustainability perspective, the concept represents an upcycling route that combines a simple mechanical recycling step with the architecture of a highly stiff reinforcement system. In contrast to the incorporation of recycled fillers directly into the bulk matrix, the sandwich design can tolerate lower quality of the recycled phase because flexural stiffness and strength are governed predominantly by the face sheets [5, 6]. Future work should therefore focus on controlling the properties of the recycled PU fraction, particularly particle size distribution, moisture content, and surface condition, as well as on implementing controlled consolidation strategies and interface modification approaches, such as compatibilising additives or a thin toughened resin interlayer, in order to improve consistency and scalability towards structural sandwich panels.

#### 5. CONCLUSION

A pilot carbon/epoxy sandwich composite with a core made from mechanically recycled polyurethane chips generated during machining was successfully manufactured by hand lay-up with vacuum assistance and subsequently evaluated by three-point bending in accordance with ISO 178. The density of the fabricated sandwich composite was  $1065 \text{ kg}\cdot\text{m}^{-3}$ . The flexural response demonstrated feasible shear transfer through the recycled core, with the maximum flexural stress ranging from 52 to 132 MPa (mean value  $88 \pm 28 \text{ MPa}$ ,  $n = 7$ ). The principal limitation was the pronounced scatter caused by non-uniform distribution of the particulate core and variable resin infiltration, which resulted in combined failure involving core crushing/shear failure and face-sheet cracking accompanied by local face sheet/core debonding. Nevertheless, the results support the proposed innovative concept of upcycling PU machining waste into lightweight sandwich cores and identify clear optimisation pathways, including control of core particle characteristics, consolidation, and interface engineering, that are necessary to achieve robust and reproducible properties.

## ACKNOWLEDGEMENTS

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