

Mechanical and Thermo-Mechanical Recycling of Polyurethane Waste Generated during CNC Machining of Tooling Boards

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Summary

Polyurethane (PU) tooling boards generate clean pre-consumer waste during CNC machining, but crosslinked PU cannot be remelted like thermoplastics. This preliminary proof-of-concept study evaluates two simple recycling routes for chips from rigid SB-0140 and SB-0600 boards: thermo-mechanical hot pressing without binder and cold pressing with binder followed by optional epoxy sealing. The exploratory matrix was not statistically replicated; therefore, the results are reported as qualitative observations of compactness, apparent porosity, machinability and surface integrity. Hot pressing gave the most coherent blocks, while cold pressing was feasible mainly at higher nominal pressure and with crushed feedstock. Epoxy sealing improved the surface of cold-pressed blocks. The results indicate possible internal recovery of clean PU tooling-board waste as non-structural semi-finished blocks, but not certified material-property data. Further work should quantify density, porosity, mechanical properties, dimensional stability and surface durability on replicated specimens.

Keywords: polyurethane waste; tooling boards; mechanical recycling; compression moulding; epoxy sealing

Introduction

Polyurethanes are widely used in tooling, transport, automotive and building applications because their density, stiffness and thermal behaviour can be tailored for many products^{1, 2}. Their end-of-life management is nevertheless difficult, particularly for crosslinked foams and rigid tooling boards, which cannot be remelted and reshaped like thermoplastics^{1, 2, 9}. PU waste can be treated by disposal, energy recovery, mechanical recycling or chemical recycling. Chemical routes such as glycolysis can recover polyol-rich fractions, but their usefulness depends on waste purity, formulation and logistics^{2, 3, 9, 10}. Mechanical recycling is simpler and is especially relevant for clean pre-consumer streams with limited sorting and contamination issues^{1, 3, 4}.

Mechanical routes usually include size reduction, densification, rebonding with a binder, adhesive pressing or compression moulding^{1, 4, 7, 9}. Product quality is affected mainly by particle size, bulk density, binder distribution, temperature and compaction pressure⁴⁻⁷, which is important because PU foam waste has low bulk density and high transport volume. Most published work concerns flexible foams, insulation products or mixed PU waste^{3, 5, 6, 8}. Less attention has been paid to clean chips from rigid polyurethane tooling boards used for models, patterns and moulds. This stream is generated on site, has a relatively stable composition and could be returned to the same workshop as secondary semi-finished material. This work therefore focuses on dry chips from two rigid PU board grades, SB-0140 and SB-0600. The waste was crushed where needed and processed by cold pressing with binder, thermo-mechanical compression moulding and optional epoxy surface sealing. Typical source chips are shown in Figure 1.

The aim was to assess, at proof-of-concept level, whether internal PU tooling-board waste can be converted into machinable semi-finished blocks. Particle size, processing route, board grade and epoxy sealing were considered as qualitative factors. The study was not a replicated optimization or standardized material characterization; it identifies feasible routes and limitations for follow-up testing.



Figure 1: Chips from CNC machining of PU tooling boards.

Materials and Methods

Source material and waste preparation

The input material consisted of chips and fragments from rigid PU tooling boards SB-0140 and SB-0600, which differ in density and mechanical performance and are used mainly for models, patterns and moulds. The waste contained fine dust, loose particles and coarse chips. Before pressing, it was sieved and, where needed, crushed to improve mould filling and compaction. Part of the SB-0140 waste was kept as coarse non-crushed chips to assess the qualitative influence of particle size during cold pressing.

The feedstock was therefore evaluated in two practical categories: coarse non-crushed chips and crushed feedstock. Detailed particle-size distribution, including fines, remains a parameter for future optimization. The processing variants were prepared to verify feasibility and obtain comparative technological observations. They were not produced in a statistically evaluable number of replicates; therefore, no variability or confidence intervals are reported. Terms such as better or improved refer only to qualitative comparison within this material set.

This preparation is important because particle size affects bulk density, interparticle contact, binder distribution and final porosity⁴⁻⁶. The crushed feedstock is shown in Figure 2.



Figure 2: Crushed PU feedstock: SB-0600 (left) and SB-0140 (right).

Final machining of recycled blocks

After pressing and, where applicable, epoxy sealing, the blocks were machined to assess machinability, edge stability and surface integrity. The conditions in Table 1 refer to this final machining step, not to generation of the original PU chip waste. The source waste originated from routine dry CNC machining, but the original cutting conditions were not reconstructed as controlled variables; therefore, their effect on recyclability cannot be evaluated here.

Table 1: Cutting conditions for final machining of pressed PU blocks.

Tool	Board	ap (mm)	ae (mm)	Vc (m/min)	fz (mm/tooth)
Toroidal end mill D20 R4	SB-0140	15	8	500	0.30
Toroidal end mill D20 R4	SB-0600	15	6	600	0.30
Ball-nose end mill D12	SB-0140	15	0.5	600	0.25
Ball-nose end mill D12	SB-0600	15	0.5	700	0.20
Flat end mill D16	SB-0140	15	5	600	0.30
Flat end mill D16	SB-0600	15	5	700	0.20

These values are representative settings for the post-pressing machining assessment. They improve transparency of the machinability evaluation but were not systematically varied and were not used to produce the original chip waste.

Hot pressing without binder

For thermo-mechanical recompression, crushed PU feedstock was placed into a steel mould of approximately 100 × 100 × 150 mm (Figure 3). The mould was heated in a laboratory furnace and compacted using a hydraulic press. Trials were performed at about 220 °C for SB-0140 and 300 °C for SB-0600, followed by compaction during cooling. These exploratory, grade-specific temperatures were not optimized or directly compared.

Because elevated temperature was used, this route is better described as thermo-mechanical compression moulding. No depolymerization or reactive recycling agent was intentionally applied, but thermally induced interfacial changes cannot be excluded without FTIR, DSC or TGA. The absence of a common temperature matrix for both grades is a limitation.

This route corresponds to compression moulding of recycled polyurethane, where temperature and pressure may support interparticle bonding without added binder^{4,7}. Representative blocks are shown in Figure 4.

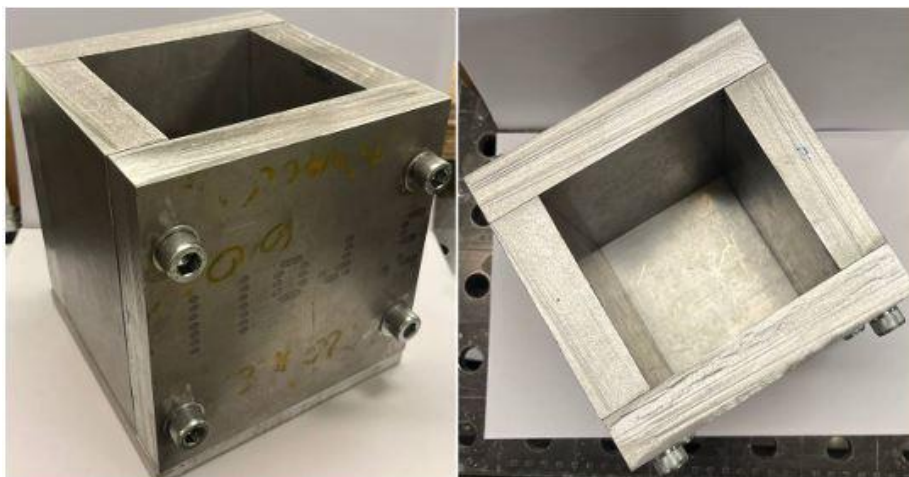


Figure 3: Steel mould for recycled blocks.

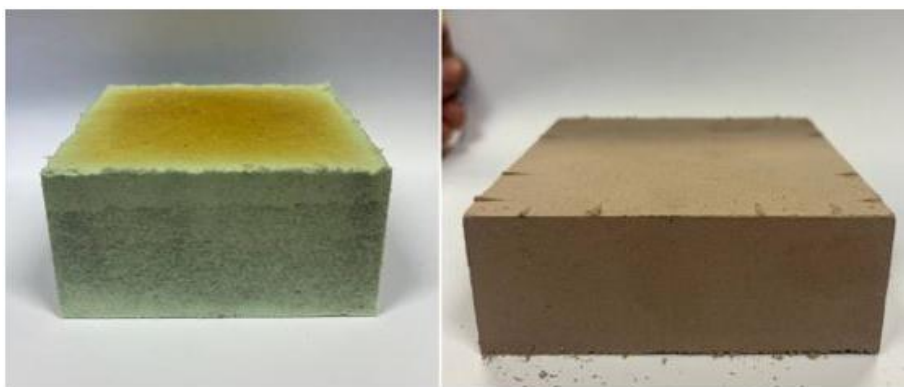


Figure 4: Hot-pressed recycled blocks: SB-0140 (left) and SB-0600 (right).

Cold pressing with binder

In the second route, crushed or uncrushed PU waste was mixed with a commercial penetration/binder system and compacted at room temperature. Pressing variants are reported as nominal pressures calculated from the applied force and the 100×100 mm mould cross-section: 4.9, 9.8 and 14.7 MPa for coarse SB-0140 chips, and 14.7 MPa for crushed SB-0140 and SB-0600 feedstock (Figure 5).

The binder amount was selected practically to wet the particles and enable compaction; dosage, uptake and distribution were not optimized or quantified. The results therefore indicate processability and surface response, not a final formulation. After demoulding, the blocks cured for at least seven days under laboratory conditions. A representative SB-0600 block is shown in Figure 6. This route is related to rebonding and adhesive pressing^{1,4}.

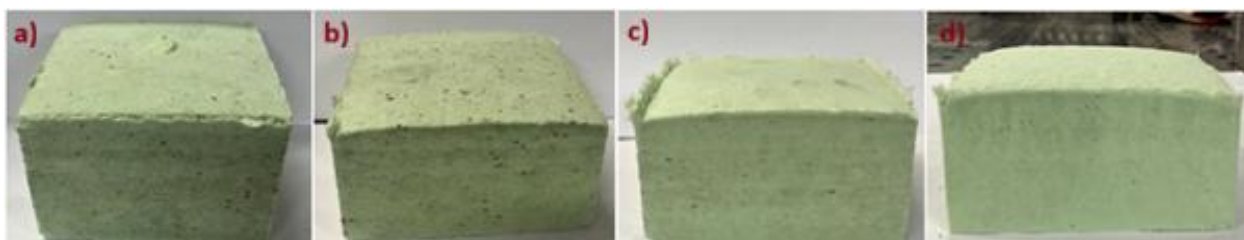


Figure 5: SB-0140 cold pressing with binder: coarse chips at (a) 4.9, (b) 9.8 and (c) 14.7 MPa; crushed chips at (d) 14.7 MPa.

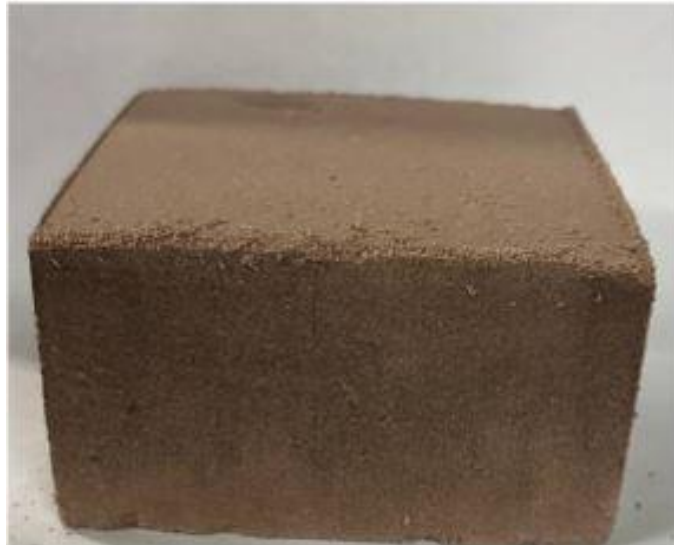


Figure 6: Cold-pressed block from crushed SB-0600 chips with binder.

Epoxy surface sealing

Because cold-pressed samples had a porous and fragile surface, the outer layer was strengthened by epoxy impregnation. LH 288 resin with H 146 hardener was applied in one or two layers, followed by light sanding. A second layer was used where the first coating was absorbed into open pores.

This post-treatment was intended to reduce open porosity and improve surface integrity, not to alter the bulk structure.

Evaluation approach

The observations are qualitative because this phase documented visual compactness, machinability, edge stability and surface appearance rather than standardized material properties. No numerical density, porosity, roughness, strength or durability values were measured. Ratings in Table 2 are comparative within this material set and do not represent certified performance levels.

Results and Discussion

Performance of hot-pressed blocks

Within the tested conditions, hot pressing appeared to provide the most compact bodies. Both foams consolidated into coherent blocks without added binder. SB-0140 showed acceptable machinability and no obvious internal separation, whereas denser SB-0600 appeared more compact and gave better edge stability and a smoother machined surface.

This agrees with reports on compression-moulded PU recyclates, where fine feedstock, temperature and pressure may support dense products^{4, 7}. For clean tooling-board waste, the route is relevant because it avoids added binder, but density, dimensional stability and mechanical properties must still be quantified. Machined products are shown in Figures 7 and 8.

The different temperatures were exploratory. The higher temperature for SB-0600 may reflect its higher density and lower compressibility. Because no temperature matrix was performed, the response of SB-0140 at 300 °C or SB-0600 at 220 °C cannot be concluded.

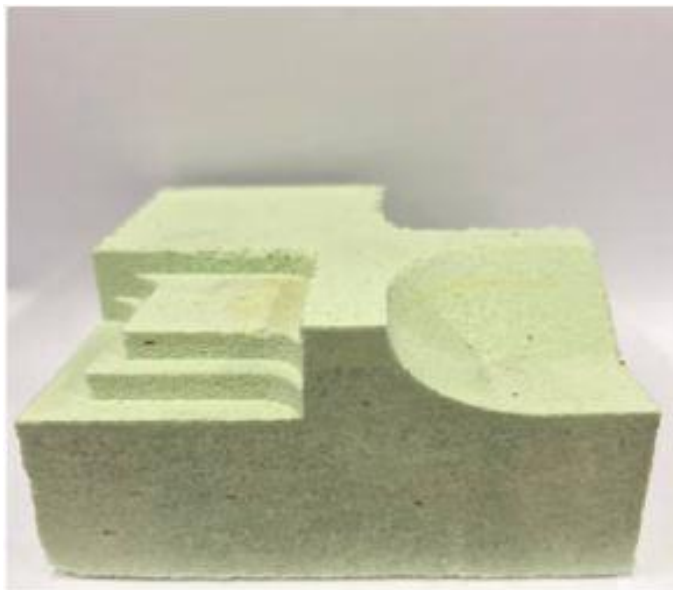


Figure 7: Machined semi-finished product from recycled SB-0140.

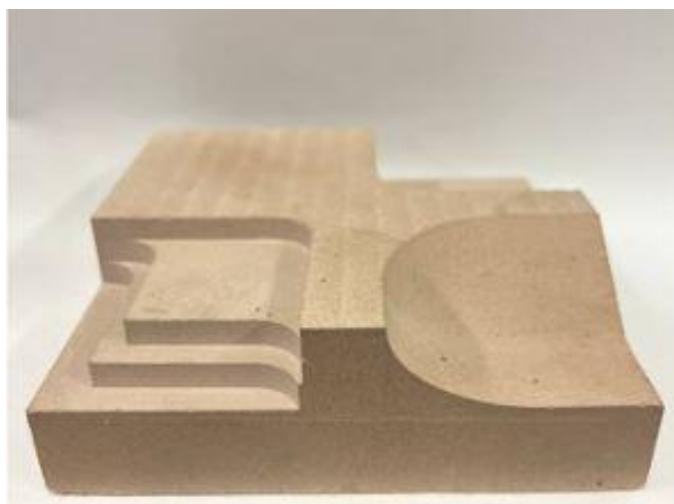


Figure 8: Machined semi-finished product from recycled SB-0600.

Effect of pressure and particle size during cold pressing

Cold pressing with binder also produced coherent blocks, but quality depended on pressure and feedstock morphology. Coarse SB-0140 chips at lower pressure showed more visible voids and local pull-out during machining. Higher pressure improved compactness, while crushed feedstock gave the most uniform SB-0140 structure (Figure 9).

Finer particles can improve packing, contact area and binder coverage. In SB-0140 they may fill voids and reduce macroporosity, improving edge stability. Too many fines, however, may increase binder demand, trap air and create weaker dust- or binder-rich zones. Particle-size distribution should therefore be optimized, not simply minimized^{1, 4, 5}.

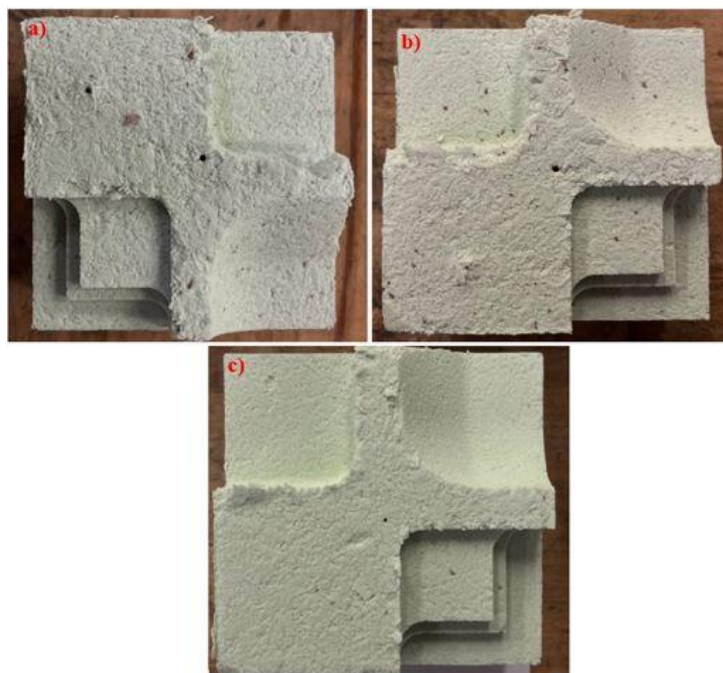


Figure 9: Machined cold-pressed SB-0140 blocks from coarse chips at (a) 4.9, (b) 9.8 and (c) 14.7 MPa.

Influence of input foam grade

Higher-density SB-0600 showed more favourable qualitative behaviour than SB-0140 in both routes. In cold pressing, crushed SB-0600 with binder gave a visually more compact block with lower apparent porosity and better edge integrity than comparable SB-0140 samples. Examples are shown in Figures 10 and 11.

The initial board grade therefore remains important. The better SB-0600 behaviour is probably linked to higher density, more compact particles, lower elastic recovery and improved contact between particles. Lower-density SB-0140 likely retains more internal porosity and larger interparticle voids, especially as coarse chips. Separate recycling streams may therefore be useful.



Figure 10: Machined SB-0140 block pressed at 4.9 MPa.



Figure 11: Machined SB-0600 block from crushed feedstock pressed at 14.7 MPa.

Surface consolidation by epoxy impregnation

Epoxy treatment visibly improved cold-pressed samples. The first coating penetrated the porous surface and a second layer closed residual pores. After curing and sanding, surfaces were smoother, less friable and easier to finish. This should be quantified by roughness, water uptake or abrasion tests.

This is relevant for patterns, temporary moulds and support tooling, where surface quality matters. The additional step and material should be included in future cost and life-cycle assessments.

Practical implications and limitations

The observations suggest that clean internal PU machining waste may be converted into semi-finished blocks instead of mixed polymer waste. This agrees with the view that mechanical recycling can be favourable for clean, homogeneous streams^{1, 3, 8}. Economic and environmental benefits still require cost and life-cycle assessment.

Within the tested variants, SB-0600 appears more suitable for semi-finished products requiring better edge integrity and lower visible porosity. SB-0140 may fit less demanding support or filling applications, especially with crushed feedstock, higher pressure and epoxy sealing.

Recycled blocks should be considered mainly for non-structural, low-load uses such as model-making blanks, temporary patterns, auxiliary tooling, support blocks, fixtures and prototype boards. Precision moulds, thermally loaded moulds, structural parts or long-term service components require validation of density, stability, strength, durability and ageing resistance.

The study remains a proof-of-concept: evidence is qualitative and not statistically replicated. Validation should include density, porosity, compressive and flexural strength, abrasion resistance, dimensional stability and service-cycle durability. Binder dosage, dwell time, hot-pressing temperature and particle-size distribution also need optimization.

Table 2: Qualitative comparison of recycling routes and observed product quality.

Route	Material / condition	Main observations	Rating
Hot pressing	SB-0140; ~220 °C	Coherent block; good machinability; minor residual porosity.	Good
Hot pressing	SB-0600; ~300 °C	Coherent block; stable edges; smoothest machined surface.	Very good
Cold pressing + binder	SB-0140 coarse chips; 4.9 MPa	Coherent but porous; larger voids and local pull-out.	Moderate
Cold pressing + binder	SB-0140 coarse chips; 9.8–14.7 MPa	Higher pressure improved compactness; less uniform than crushed feedstock.	Good
Cold pressing + binder	SB-0140 crushed feedstock; 14.7 MPa	More uniform structure; smaller visible pores; benefits from epoxy sealing.	Good-very good
Cold pressing + binder	SB-0600 crushed feedstock; 14.7 MPa	Low visible porosity; strong edge integrity; one epoxy layer often sufficient.	Very good

Note: ratings are qualitative assessments from visual inspection and machining response. No standardized mechanical testing or statistically evaluable replication was done.

Conclusion

This proof-of-concept study indicates that PU waste from CNC machining of rigid tooling boards can be converted, under the tested exploratory conditions, into coherent semi-finished blocks. Thermo-mechanical hot pressing without binder gave the most favourable qualitative combination of compactness, cohesion and surface quality. Cold pressing with binder was also feasible but more sensitive to particle size and pressure and benefited from epoxy sealing. These observations indicate process feasibility, not quantitative material qualification.

The denser SB-0600 feedstock gave the most promising qualitative products, indicating that source-board density affects recycling performance. The investigated routes may reduce disposal volume and retain some material value of clean PU scrap, especially for non-structural model-making and auxiliary tooling.

Follow-up work should quantify density, porosity, compressive and flexural properties, dimensional stability, surface roughness and machining performance on replicated specimens. It should also compare both grades at identical hot-pressing temperatures and optimize binder dosage, dwell time and particle-size distribution.

Acknowledgment

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Mechanická a termo-mechanická recyklace polyuretanového odpadu vznikajícího při CNC obrábění modelářských desek

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Souhrn

Polyuretanové (PU) modelářské desky vytvářejí při CNC obrábění čistý předspotřební odpad, který nelze kvůli zesítné struktuře znovu tavit jako termoplasty. Tato předběžná koncepční studie hodnotí dvě jednoduché recyklační cesty pro třísky z desek SB-0140 a SB-0600: termo-mechanické lisování za tepla bez pojiva a lisování za studena s pojivem, případně doplněné epoxidovým utěsněním povrchu. Experimentální matice nebyla statisticky opakována, proto jsou výsledky prezentovány jako kvalitativní pozorování kompaktnosti, zdánlivé pórovitosti, obrobiteľnosti a integrity povrchu. Lisování za tepla poskytlo nejkompaktnější bloky, zatímco lisování za studena bylo použitelné hlavně při vyšším nominálním tlaku a s drcenou surovinou. Epoxidové utěsnění zlepšilo povrch bloků lisovaných za studena. Výsledky naznačují možnost interního využití čistého PU odpadu.

Klíčová slova: polyuretanový odpad; modelářské desky; mechanická recyklace; lisování; epoxidové utěsnění