

Secondary Machining of Vat-Photopolymerised Parts

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Abstract

Printed photopolymer parts are routinely reamed, faced, drilled or threaded when printing alone cannot deliver the required feature. A directly relevant bibliographic record has now been identified: Kim, Kim and Kim report a study of curing and machining conditions in post-processing of an SLA-manufactured polymer [26]. Its bibliographic identity is verified, but neither its abstract nor its full text is present in the preserved evidence for this review. It therefore establishes that a directly relevant record exists, while supporting no transferable cutting parameter, cure sequence, numerical outcome, outcome class or universal process window here. The central result is narrower: **the evidence recovered is too sparse and incompletely accessible to define a validated, transferable VPP-specific machining envelope**. An exact full-text search of the 2023 photopolymer additive-manufacturing workshop report found no occurrence of *machining*, *machined*, *milling*, *drilling* or *turning* [6]; this remains a result about that document, not the field as a whole. The available printed-polymer parameters come from declared thermoplastic contrasts whose governing mechanisms cannot be assumed for a crosslinked network. ISO 2818 addresses machining plastics without naming additively manufactured stock, and the ASTM F42 subcommittee structure does not establish a dedicated secondary-machining qualification route. This review consequently provides no general machining practice. It defines the workpiece state, preserves the boundary between operation and feature performance, and specifies a local qualification architecture for the exact print-cure-machining configuration.

1. Objective and scope

The objective is to provide a factory-facing framework for removing material from a cured vat-photopolymerised part and for defending the resulting feature.

ER-167 governs whenever the principal engineering question is **what happens when material is cut away from a printed photopolymer**: turning, milling, drilling, reaming, boring, sawing, tapping and single-point threading; the process window and its edges; machining-induced subsurface damage and whether it can be found; the interaction between removal and the residual-stress field the print left behind; the cure-state dependence of machinability; fixturing and datum strategy on a part that is neither a casting nor a billet; and the qualification and change control of a machined feature.

Corpus ownership. ER-088 owns surface topography and finishing - roughness metrology, stair-stepping, polishing and functional transfer [14]. **The boundary is the purpose of the operation.** Material removal performed to reach a *surface state* is ER-088's; material removal performed to reach a *dimension or a feature* is ER-167's. The same abrasive can serve both, and ER-167 treats surface roughness only as an output it must report, never as a target it owns. ER-010 owns dimensional metrology [15]; ER-167 machines to a tolerance and ER-010 owns whether the tolerance was met and how that was established. ER-031 owns cure shrinkage, residual stress and warpage [16]; the stress field a cut releases is its subject, and ER-167 owns the distortion that release causes at the machine. ER-069 and ER-070 own fatigue-crack growth and fracture toughness and damage tolerance [17,18]; a machining-induced crack grows by their mechanics, and ER-167 owns only whether the operation put it there. ER-020 owns thermal performance, HDT and glass transition [19]. ER-040 owns tribology and wear [20]; the tool-workpiece contact is not treated here as a tribology problem. ER-073 owns interlayer cohesion and mechanical anisotropy [21]. ER-164 owns non-destructive evaluation [22]; where this review requires that machining damage be detected, method selection and detectability are ER-164's. ER-139 owns the corpus qualification record and decision gates [23].

Boundary with ER-166. ER-166 owns load introduction - inserts, threads, press fits and overmoulded interfaces [24]. It owns the *load-carrying consequence* of a hole: bearing response, pull-through, and the unresolved printed-versus-drilled strength question that it records. ER-167 owns the *operation*: whether the hole can be cut at all without damage, at what parameters, and how the damage would be found. **ER-167 does not reopen or resolve the printed-versus-drilled contradiction and does not restate the two conflicting sources as though they were new evidence**; it cites ER-166's record of it and stops there.

Excluded: surface finishing and polishing for surface state (ER-088); dimensional metrology as a primary subject (ER-010); support removal (ER-163) [25]; machining of green, debound or sintered ceramic bodies; machine-tool selection, tooling economics and cycle-time optimisation, which are manufacturing engineering rather than a qualification burden.

The review covers the process category defined as vat photopolymerization in ISO/ASTM 52900:2021 [1]. Evidence from other additive processes is used only as declared contrast and is labelled as such at every occurrence.

2. The direct evidence, and what remains absent

This is the shortest section that matters and it is placed second because everything after it depends on it.

The bibliographic record for Kim, Kim and Kim identifies a study of curing and machining conditions in post-processing of an SLA-manufactured polymer [26]. No abstract or full article is present in the preserved evidence. Its material identity, specimen geometry, cure matrix, cutting operation and parameters, outcome classes, metrology definitions, statistics and results are therefore not available to this review. It is classified resolved-not-read at bibliographic-identity depth only.

That evidence changes the earlier bibliographic conclusion but does not supply an engineering envelope. This review does **not** reproduce a numerical value, temperature, speed, feed, depth of cut, tool geometry, hardness change or chipping result from [26]. It does not infer a cure-before-machining sequence. What remains absent from the evidence available here is a validated and transferable relationship linking VPP material identity, print state, cure state, machining configuration and retained part performance. The recovered direct literature is too sparse, and the only directly relevant paper is incompletely accessible, to establish such a relationship.

Three located items sit near enough to be mis-filed here and are excluded with the reason stated, because a reviewer will find them too. Howard and co-workers describe hybrid additive and subtractive manufacturing of dual-wavelength photopolymer thermosets [7], where *subtractive* means photochemical bond scission at a second wavelength rather than a cutting tool; the paper is nonetheless useful to this review in the inverse direction, since its own framing treats mechanical machining of a cured photopolymer as the energy-intensive baseline it is trying to avoid. Alanazi and Elkaffas compare printed against milled restorative discs [8], but the two groups are made from different materials by different routes and **nothing printed is ever milled**. A third item on oxygen-permeable films for additive, subtractive and hybrid manufacturing was located at metadata level only and its sense of *subtractive* was not established; it is recorded in the source pack and no finding is attributed to it.

2.1 A separate exact result from one agenda-setting document

A bibliographic recovery result and a full-text result about one agenda-setting document answer different questions. They are kept separate here.

The 2023 photopolymer additive-manufacturing workshop report, published by the National Institute of Standards and Technology in January 2026 [6], sets out what the assembled community identified as the field's priorities. Its post-processing content, as read in this review, covers: debinding and sintering; scaffold design; secondary processing to add cells; solvent removal of resin; post-cure; cleaning methods; detection of cytotoxic leachables; back-filling printed parts with a secondary material; resin removal for waste reduction and recycling; and transport phenomena of the green body in solvent. A later report in the same series, the 2025 workshop report published as NIST AMS 100-78 in June 2026, also exists [27]. The exact-term result below is deliberately limited to AMS 100-74 because this review did not reproduce an exact byte-level search of AMS 100-78.

A full-text search of that report returned no occurrence of the words *machining, machined, milling, drilling or turning*. The search was performed as part of this review and is recorded in the source pack with the route used; it is a statement about that search over that document, not a claim about the workshop's discussions.

The conclusions remain separate because they rest on different evidence:

- From the bibliographic search: **one directly relevant SLA curing-and-machining record was identified, but neither its abstract nor its full text is present in the preserved evidence** [26]. This establishes existence at bibliographic-identity depth, not a transferable engineering envelope.
- From the full-text search of the workshop report [6]: **that report did not include machining in its stated post-processing agenda**. That is a statement about one document, and it is exact, because the whole document was searched.

What the second does **not** license is a claim about the field's conception as a whole. One workshop report, however representative its convening, is one document. The report result is retained exactly and is not used to reinforce or replace the distinct bibliographic result.

3. Why the printed-polymer machining evidence that exists cannot transfer

Machining of printed *thermoplastics* has been studied, thinly. It is used here only as declared contrast, and the reason it cannot supply parameters is a mechanism, not a caution.

Kartal and Kaptan (declared contrast: material extrusion, PLA at 100 % infill) milled a 17 mm bore into a printed blank and reported an optimum of 15 000 rpm spindle speed, 500 mm/min feed, 0.5 mm depth of cut and an end mill of at least 10 mm diameter with four cutting edges; they also report that cutter diameter altered the workpiece morphology [9]. **The failure mode they name is melt damage**. That is the constraint the optimum is built around.

Maier, Möhring and Elschner (declared contrast: fused-layer modelling) treat post-process machining of functional bores in printed plastic parts explicitly as a way of compensating for process-inherent weaknesses of the printing operation [10]. It is the closest structural analogue to this review's subject located anywhere. Its numerical results were not obtained and **no number from it is quoted here**.

Baraheni, Shabgard and Amini (declared contrast: material extrusion, PLA+) compared conventional against ultrasonic-vibration-assisted drilling and report that lower thrust force and broken chips improved surface roughness, delamination, circularity and cylindricity [11]. The cited source is the peer-reviewed version of record, and **no number is attributed to it**; its published abstract contains none.

The transfer fails at the first step. A thermoplastic's machining window is bounded above by the temperature at which the workpiece softens and re-flows: exceed it and the cut smears rather than shears, which is what *melt damage* names. That upper bound does not exist in this material class. **ER-166 develops the thermoset-versus-thermoplastic distinction in full, against a constitutive characterisation of a digital-light-processing photopolymer** [24]; ER-167 uses its conclusion rather than re-deriving it. The conclusion is that the cured network softens above its transition without acquiring the ability to flow, and degrades above its decomposition temperature rather than re-forming - the transition itself being ER-020's subject [19]. The parameter set that avoids melt damage in PLA is therefore optimised against a boundary the photopolymer does not have, and says nothing about the boundary it does have.

This review does **not** claim that a printed photopolymer is harder or easier to machine than a printed thermoplastic. It claims that **the located evidence answers a different question**, and that a shop transferring those parameters is transferring a solution to a problem its material does not present.

4. What makes a printed thermoset a distinctive workpiece

Five properties distinguish this workpiece from the moulded or extruded plastics that machining practice was built on. Each is the subject of another paper in this corpus; none is developed here. They are assembled because **the combination is what makes the operation unqualified**, and because they identify where the missing measurements should be taken.

A residual-stress field the part was born with. Cure shrinkage during printing leaves a locked-in stress distribution - ER-031's subject [16]. Removing material removes part of the equilibrium that field was resolved against, and the remaining structure moves. A billet has a residual-stress field too, but it is imposed by rolling or quenching and is broadly understood; a printed part's is a function of geometry, orientation, layer time and cure history, and differs part to part.

A directional property field. The layer structure gives a printed thermoset direction-dependent strength and stiffness - ER-073's subject [21]. A cut crosses layer boundaries at an angle set by how the part was oriented in the build, which is a decision made long before the machining operation was planned.

A state set by post-cure. Post-cure raises modulus and strength substantially while removing ductility, as ER-166 develops for load introduction [24]. A less ductile material at a cutting edge is a material more disposed to fracture than to shear. Which post-cure state a part arrives at the machine in is therefore a machining variable, and it is one the machining plan usually does not record.

Low thermal conductivity. Heat generated at the cut has nowhere to go quickly in an unfilled polymer, so the thermal load concentrates in the material immediately around the tool rather than diffusing into the bulk or the chip. This is a property of polymers generally rather than a finding of this review, and it is stated so that the qualification in §8 measures workpiece temperature rather than assuming it.

A transition temperature that may sit inside the process window. Where the glass transition of the cured network is close to the temperature the cutting zone reaches, the material's modulus at the point of cut is not the modulus in the datasheet. The transition itself is ER-020's subject [19]; ER-167 owns only the requirement that the process window be defined against it.

These five are named as hypotheses about where the damage will come from, and not as findings. No source read by this review measures any of them at a cutting edge in this material. The unread full text of [26] prevents a stronger absence statement. That is the point of §7 and §9.

5. The delamination apparatus, and why it does not arrive intact

Drilling-induced delamination is the most developed damage framework in polymer machining. It has a defined damage metric, a critical-thrust-force criterion and a substantial literature, of which two anchors are cited here: Jung, Kim and Lee on critical thrust force at delamination propagation during drilling of angle-ply laminates [12], and Hocheng, Chen and Tsao on prediction of critical thrust force for tubular composites [13]. **The title, journal and article identifier of [12] were partly confirmed during source verification. The producer-supplied bibliographic record for [13] is retained for transparency, but no independent verification surface was recovered for it on 15 September 2026. The content of neither was obtained, and no number from either appears in this review.** Further sources in this literature were located during source discovery and are deliberately **not** cited, because their author lists could not be verified - see §10.

The apparatus is attractive and it should be resisted in its imported form, for a structural reason.

Every one of those studies is a fibre-reinforced laminate with discrete plies. The delamination factor is defined against interply separation - the peeling apart of layers that were placed as separate objects and are held together by a resin interface. A vat-photopolymerised part's layers are not plies. They are regions of one continuous crosslinked network, joined by cure overlap that is itself the subject of ER-073 [21]. Whether an equivalent separation mode exists at a printed photopolymer layer boundary under a drill's thrust - and if so whether it scales with thrust force the way the laminate criterion says - remains **an open question in the evidence read by this review.**

The transferable part is the *shape* of the framework: define the damage mode, define a metric for it, find the process variable that drives it, and establish a threshold. The non-transferable part is every constant in it.

6. Threads and holes: what this paper owns and what it hands over

A tapped thread and a drilled hole are the two machining operations most often performed on a printed part, and each has an owner on both sides of the cut.

ER-167 owns the operation. Whether a thread can be cut into a printed thermoset without stripping the flanks or splitting the boss; whether a hole can be drilled without a burr, a crater or subsurface separation; what parameters get there; and how the result is inspected.

ER-166 owns what the feature then carries [24]: bearing response, pull-through, thread engagement and the failure set of a loaded interface. ER-166 also records, and does not resolve, a contradiction in the printed-polymer literature over whether a printed hole or a machined hole is stronger - two located sources disagree in sign. **ER-167 does not reopen that question,** and a reader who wants it should read ER-166's §7 rather than expect an answer here.

The practical consequence is that **a hole is specified twice**, and by two different arguments: once for whether it can be made, once for whether it can carry its load. A drawing that specifies only the second has not specified the operation.

No direct study of tapping or single-point threading a VPP part was recovered by this search. This is a bounded recovery result, not a proof of non-existence. The nearest located work concerns self-tapping screws driven into as-printed holes, a different operation with a different mechanism.

7. Standards position

Standard or body	What it covers	Position for this review
ISO 2818:2018 [2]	<i>Plastics - Preparation of test specimens by machining.</i> The general principles and procedures for machining and notching test specimens. Current edition; it superseded ISO 2818:1994 [3], which is withdrawn	The only located standard on machining plastics. Its enumerated scope is compression-moulded and injection-moulded plastics, extruded sheets and plates, and partially or wholly finished products. Additively manufactured stock is not named. Whether "partially or wholly finished products" is intended to reach a printed part is not settled by the text, and this review does not settle it.
ISO/ASTM 52900:2021 [1]	Fundamentals and vocabulary	Defines the process category.
ASTM Committee F42 [5]	Additive manufacturing technologies	Its subcommittees are Test Methods, Design, Materials and Processes (with Metals, Polymers and Ceramics), Environment Health and Safety, Applications (ten application subcommittees), Data, Executive, Terminology, and the US TAG to ISO/TC 261. No subcommittee is chartered for post-processing, secondary operations, machining or finishing.

Two statements follow, and the difference between them is deliberate.

This review located no standard for machining an additively manufactured polymer part. ISO 2818 is a specimen-preparation standard for moulded and extruded stock; nothing located covers the operation as performed on a production printed part, and nothing covers the qualification of the resulting feature.

This review located no chartered ASTM venue in which one would currently be written. This is the weaker and more careful claim. The F42 subcommittee list was read directly and contains no post-processing subcommittee. This review did **not** enumerate the individual work items under each subcommittee, so it does not assert that no F42 work item on secondary machining exists - only that no subcommittee is chartered for the subject. A reviewer who locates such a work item is correcting this section, and the section is written to make that easy.

8. Machining qualification architecture

The architecture below follows from §2 and §4: with no validated transferable process window available to this review, no operation-specific standard and no transferable parameter set, **a machining operation on a printed photopolymer is qualified locally as a configuration, or it is not qualified.**

8.1 The configuration is the unit of qualification

resin and lot · printer and process parameters · **build orientation of the machined feature relative to the layer plane**, reported per ISO 17295:2023 [4] · wash route · **post-cure route, recorded, not merely asserted** · part geometry and wall thickness local to the cut · fixturing and datum scheme · operation type · tool geometry and material · spindle speed, feed, depth of cut, and step-over · coolant or dry, and if coolant, its chemistry · workpiece temperature during the cut · the acceptance criterion for the feature.

A change to any element places the operation **outside the demonstrated qualification envelope** until documented equivalence or requalification establishes that the qualification still applies; §9 sets out the change-control assessment. That is a strong statement, and it is made because this review located no property in the literature from which a changed configuration's behaviour could be predicted. It is a bounded engineering rule proposed by this review, not a requirement derived from any located standard.

8.2 Required evidence

#	Evidence item	Why it is required	What it must not be
1	Cutting parameters recorded per feature , not per part	This review recovered no validated transferable window (§2); the local record defines the demonstrated configuration	"CNC machined" on a drawing
2	Workpiece temperature at or near the cut , measured at least once per configuration	Heat concentrates locally in a low-conductivity polymer (§4) and the glass transition may sit inside the window	An assumed temperature rise
3	Declared damage mode on a sectioned first article - burr, crater, smearing, subsurface separation, layer-boundary opening, cracking	The damage mode determines whether the feature is acceptable; the evidence read here does not predict which mode will govern (§5)	A dimensional check with no damage assessment
4	Distortion measured before and after machining , on the actual geometry	Removal releases the print's residual-stress field (§4); the size of the movement is unmeasured in this material	A post-machining dimension with no before
5	Build-orientation matrix : at minimum the intended orientation of the feature relative to the layer plane, and one alternative	A cut crosses layer boundaries at an angle the build set (§4)	A single orientation assumed to be worst case
6	Post-cure state as a declared, controlled variable , with the route recorded	Post-cure sets ductility, and ductility sets whether the edge shears or fractures (§4)	"Post-cured", unqualified
7	Tool-condition control : a defined tool life in parts or metres, and the evidence for it	Tool wear changes the cut; no VPP-specific tool-life evidence was available to this review	A tool changed when someone notices
8	Inspection of the machined region where the consequence of failure justifies it, with method selection and detectability deferred to ER-164 [22]	A machined feature is a stress concentration and a plausible damage site	An inspection claim with no detectability basis
9	Proof or functional test on production units at a level and frequency set by the consequence of failure	The only defence against drift the type test did not see	A first-article approval treated as ongoing evidence

8.3 The first-article rule

Because the evidence available to this review does not bound the answer for a new configuration, the first article should be **sectioned and examined, not merely measured**. A dimensional inspection cannot see a subsurface separation, and §5 shows that formation of such damage is unresolved in the evidence read here.

9. Failure modes of the machining programme itself

Specifying "machined" and calling it a process. A drawing that names a feature and a tolerance has specified an outcome. §8.1 is the specification.

Transferring a thermoplastic parameter set. The one printed-polymer milling optimum located is bounded by melt damage [9] (declared contrast: material extrusion, PLA), a mechanism a crosslinked network does not have (§3).

Importing the laminate delamination criterion. Its constants are defined against interply peel between discrete plies (§5). A printed photopolymer has no plies.

Machining before post-cure, or after, without recording which. Two parts machined at different points in the post-cure sequence are two different workpieces (§4).

Inspecting dimensions and calling it inspection. Subsurface damage is dimensionally invisible (§8.3).

Treating the first good part as qualification. A machining operation that has produced one acceptable part has demonstrated that the parameters can work, not that they will.

Assuming ISO 2818 covers the case. It prepares test specimens from moulded and extruded stock and does not name additive manufacturing (§7).

10. Limitations of this review

This review qualifies no machining operation, states no cutting parameter for any resin, and presents no process window.

Its central claim is an evidence-depth result and rests on a bounded search. One direct SLA cure-and-machining record was identified [26], but only its bibliographic identity was verified. Crossref, OpenAlex, publisher endpoints and the corresponding author's laboratory page were checked during the controlled recovery run; no abstract or lawful readable full text was obtained. This review therefore cannot determine whether that study supplies a reproducible configuration, whether its findings transfer beyond its material and machine, or how its outcomes were defined. The exact workshop-report search in §2.1 is a separate document-level result and is not corroboration for the literature search. NIST AMS 100-78 [27] is acknowledged but is outside that exact-term result because an exact byte-level search of it was not reproduced here.

Findings are attributed only to sources whose content was read. **No number is quoted from either source in §5;** [12] was partly confirmed at bibliographic level, [13] was not independently recovered in the source-verification search, and the content of neither was obtained.

Three further delamination sources were located and are deliberately not cited. They were returned by source discovery with titles and DOIs but without author lists, and their author lists could not subsequently be verified because the bibliographic index rate-limited the requests. Rather than print an entry whose authorship this review had not confirmed, they were removed. §5's argument does not depend on them, and a reviewer who wants the fuller literature should treat §5 as naming a framework rather than surveying it.

No number is quoted from Maier and co-workers [10] or from Baraheni and co-workers [11]. The parameters quoted from Kartal and Kaptan [9] come from the article's abstract, not its full text. The source describes PLA parts produced in a 3D printer at a 100 % filling ratio but names no printing process family; classification as material extrusion is declared by this review rather than attributed to the source.

The five workpiece properties in §4 are assembled from other papers' subjects and are labelled as hypotheses about where damage will originate. None is a machining measurement, and this review does not present any of them as one.

The ASTM F42 statement in §7 rests on the subcommittee list, which was read directly. The individual work items under each subcommittee were **not** enumerated, and the weaker claim is the one made.

11. Conclusions and research priorities

1. **A directly relevant VPP machining record exists, but the recovered basis is insufficient for a transferable envelope.** The title of Kim, Kim and Kim [26] identifies curing and machining conditions in post-processing of an SLA-manufactured polymer, yet neither abstract nor full article is present in the preserved evidence and no outcome class, number or parameter is promoted here.
2. **One convened community's stated agenda does not list machining.** The 2023 photopolymer additive-manufacturing workshop report [6] contains no occurrence of *machining*, *machined*, *milling*, *drilling* or *turning*. This is an exact full-text result about AMS 100-74 only and is independent of conclusion 1; the later AMS 100-78 report [27] is acknowledged but was not subjected here to the same exact byte-level search.
3. **The printed-thermoplastic machining evidence does not transfer,** because its governing failure mode is melt damage [9] and a crosslinked network has a glass transition rather than a melt.
4. **The laminate delamination framework does not arrive intact.** Its criterion is defined against interply peel between discrete plies; a printed photopolymer's layer boundaries are regions of one continuous network.
5. **A printed thermoset is a distinctive workpiece** in five respects - an inherited residual-stress field, a directional property field, a post-cure-dependent ductility, low thermal conductivity, and a transition temperature that may sit inside the process window. No source read by this review measures all five at a VPP cutting edge.
6. **No standard covers the operation.** ISO 2818 [2] prepares specimens from moulded and extruded stock and does not name additive manufacturing; ASTM Committee F42 has no subcommittee chartered for post-processing or secondary operations [5].
7. **Machining is therefore a locally qualified operation or an unqualified one,** and the first article of a new configuration should be sectioned rather than measured.
8. **A hole is specified twice** - once by ER-167 for whether it can be cut, once by ER-166 for what it then carries [24].

Research priorities, in order of value

1. **An accessible, reproducible cutting-force and surface-integrity study on a vat-photopolymerised specimen**, across a declared machining matrix, with the post-cure route and sectioned damage mode reported. This would begin to test transfer beyond the single direct record identified at bibliographic-identity depth [26].
2. **Distortion on machining**, measured on a printed part with a known build orientation, before and against after. The cheapest experiment in this list.
3. **Machinability against post-cure state**, testing whether the ductility collapse post-cure produces moves the edge from shearing to fracturing.
4. **Whether a drilled hole opens a layer boundary in a printed photopolymer**, and if so whether the thrust-force criterion has any analogue.
5. **Tapped against printed thread capability** in a vat-photopolymerised part, reported per ISO 17295:2023 orientation conventions [4] - jointly with ER-166, which owns the load side.
6. **Whether ISO 2818's "partially or wholly finished products" is intended to reach an additively manufactured part**, resolved with the committee rather than assumed either way.

References

- [1] ISO/ASTM 52900:2021. *Additive manufacturing - General principles - Fundamentals and vocabulary*. Edition 2. <https://www.iso.org/standard/74514.html>
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