

ER-87

Magnetically Functional Photopolymer Composites in Vat Photopolymerisation: Filler Dispersion, Cure Coupling, Magnetic State and Field-Programmed Response

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Statement of Significance

Magnetically functional vat-photopolymerised composites are often discussed through a final device response: attraction, bending, rotation, remanence, heating or electromagnetic loss. That endpoint alone does not define the magnetic material. The controlled evidence shows that the realised response depends on a chain of coupled states: magnetic phase and particle state, dispersion and sedimentation, optical-cure interaction, printed microstructure and particle orientation, magnetisation history, direct magnetic measurement and the field conditions used for functional testing.

ER-87 develops a qualification and reporting architecture for that chain. It does not prescribe one universal filler loading, exposure multiplier, magnetising field, actuation test or service-life threshold. It does not convert adjacent IEC or ASTM magnetic-measurement methods into a VPP-specific acceptance standard, and it does not absorb neighbouring reviews on generic rheology, cure-depth optics, soft robotics, shape-memory systems, electromagnetic absorption, fracture, biological response or clinical suitability. Its central contribution is a material-state gate: magnetic performance should be interpreted only when the precursor, printed, magnetised and tested states are explicitly connected.

Abstract

Vat photopolymerisation can produce magnetically functional composites with complex geometry, spatially programmed magnetic states and field-responsive behaviour. The same magnetic filler that provides function can also alter suspension stability, optical energy delivery, cure behaviour, feature fidelity and the realised particle distribution. Subsequent field-assisted alignment or post-print magnetisation can further change anisotropy and magnetic response. A magnetic-composite result is therefore conditional on more than resin identity and filler loading.

This review organises the controlled evidence into an eight-stage material-state chain: magnetic phase and particle state; dispersion, agglomeration and sedimentation; optical-cure coupling; printed microstructure and orientation; magnetisation timing and field history; direct magnetic metrics; functional response under declared field conditions; and retained magnetic, dimensional and mechanical performance. Direct VPP evidence spans circulating-vat processing, soft-magnetic ferrosilicon composites, Fe₃O₄ thiol-click photopolymers, high-loading hard-magnetic DLP systems and dynamic-field-assisted particle alignment. Shape-memory, magnetic-hyperthermia and post-pyrolysis electromagnetic-loss studies are retained only as bounded or context-only branches.

The review separates soft- and hard-magnetic measurement questions, denies evidentiary independence between two same-laboratory 2026 dynamic-field papers, and treats cycling and long-term retention as an explicit source gap rather than an inferred property. Adjacent IEC 60404 and ASTM magnetic test methods are mapped to direct magnetic measurements while their specimen-geometry, magnetic-class and circuit assumptions are preserved. A minimum reporting architecture and cross-study comparison gate are proposed so that magnetic response is tied to a reconstructable material and test state rather than to filler identity or a single demonstration.

Keywords: vat photopolymerisation; magnetic composites; digital light processing; magnetic particles; sedimentation; cure coupling; magnetic anisotropy; magnetisation; remanence; coercivity; field-assisted alignment; qualification

1. Introduction

A magnetic filler does not create a single, self-defining material state when it is dispersed in a photocurable resin and processed by vat photopolymerisation. The filler can settle, agglomerate, scatter or absorb curing light, orient under an applied field, redistribute during processing, and interact with the polymer network and printed geometry. The final part can then be magnetised before, during or after printing and tested under different magnetic circuits and field conditions. Each stage changes what a measured magnetic or functional result means.

The direct evidence illustrates these couplings from different directions. Zhou et al. addressed photon interference and rapid sedimentation in SrFe₁₂O₁₉-filled systems through circulating vat photopolymerisation, linking filler uniformity, printability and magnetic response [1]. Okoruwa et al. studied a ferrosilicon-filled VPP binder system in which solids loading, conversion, post-cure, mechanics and VSM measurements were part of the same qualification problem [2]. Rossegger et al. showed that Fe₃O₄-filled thiol-click photopolymers couple filler content with cure kinetics, viscosity, network state and magnetically driven movement [3]. Li et al. linked a high-loading hard-magnetic suspension with cure behaviour, feature fidelity, remanence and magnetisation programming [4].

More recent field-assisted DLP work adds another layer. Sun et al. used dynamic magnetic alignment to reduce aggregation and improve alignment and remanence before curing [9]. A later paper from the same research line examined rotating-field frequency as a narrower optimisation variable [6]. These two papers are mechanistically useful but are not independent corroboration; ER-87 treats them as one SAME-LAB / SAME-METHOD evidence family.

ER-87 asks one engineering question:

What minimum material-state record, direct magnetic measurement and condition-bounded functional test are required before magnetic performance from a vat-photopolymerised composite can be interpreted, compared or qualified?

The answer is not a universal recipe. It is a chain of states that must remain connected from filler to retained function.

2. Magnetic material classes and evidence states

Magnetic composites cannot be pooled merely because they respond to a magnet. Soft-magnetic, hard-magnetic and other magnetic-particle systems differ in remanence, coercivity, magnetisation history and appropriate measurement method. A material that is attracted by an external magnet is not necessarily a permanent magnet, and an actuator demonstration is not a substitute for direct magnetic characterisation.

Table 1. Magnetic terms and evidence states used in ER-87

Term or state	Operational meaning in ER-87	What it does not establish by itself
Magnetic phase	Identified magnetic chemistry/phase in the formulation or printed composite	Printed magnetic response or spatial uniformity
Suspension state	Dispersion, agglomeration, sedimentation, circulation and field-driven redistribution before cure	A valid cure window or final anisotropy
Printed magnetic state	Magnetic phase as realised in a printed geometry with a defined density, void state and particle orientation	Magnetisation history
Magnetisation state	Magnetic state created by a declared field history before, during or after printing	Functional response under a different field condition
Direct magnetic metric	M-H, remanence, coercivity, susceptibility, permeability or demagnetisation behaviour measured by a justified method	Actuation, heating, sensing or service performance
Functional response	Force, torque, displacement, deformation, heating or other response under declared conditions	Long-term retention or transfer to another resin/process
Retained performance	Magnetic, dimensional and mechanical response after declared cycling, ageing or damage	Universal service life
Manufacturer context	First-party information describing a commercial implementation	Independent validation of magnetic performance

This vocabulary is deliberately state-based. It prevents a product name, particle type or visual attraction to a magnet from being used as a surrogate for a measured magnetic material state.

3. Magnetic phase and particle state must be reported

The first qualification layer is the magnetic phase itself. At minimum, a report should identify the magnetic chemistry or phase, particle size or size distribution where available, surface treatment where relevant, particle density when it affects settling analysis, loading basis, batch identity and whether the magnetic phase is intended to behave as a soft- or hard-magnetic constituent.

The controlled sources span materially different phases. Zhou et al. used SrFe₁₂O₁₉ in a circulating-vat system [1]. Okoruwa et al. used Fe-6.5 wt%Si powder in a VPP binder study [2]. Rossegger et al. used Fe₃O₄ nanoparticles in thiol-click photopolymers [3]. Li et al. and the Sun research line address hard-magnetic particle systems in field-assisted DLP [4,6,9]. These systems should not be compared by filler loading alone because particle chemistry, density, size, magnetic class, surface state and matrix interaction can all change both processing and magnetic response.

The reporting rule is therefore:

magnetic phase identity + particle state + loading basis + batch

before any inference about printability or magnetic function.

4. Dispersion, agglomeration and sedimentation are material-state variables

A nominal filler loading does not guarantee a uniform filler distribution at the moment of exposure. Sedimentation can produce vertical or temporal concentration gradients. Agglomeration can produce local optical shielding, print defects and nonuniform magnetic response. Mixing history and waiting time can therefore be part of the material state rather than incidental laboratory detail.

Zhou et al. make this issue explicit by using circulation to counter rapid particle settling and maintain a more uniform printing environment [1]. Rossegger et al. connect filler-containing resin behaviour with viscosity and stability in a magnetoactive photopolymer system [3]. The two Sun papers address field-assisted redistribution and alignment in the same research line [6,9].

ER-87 does not duplicate the generic rheology and sedimentation treatment assigned to ER-36. Instead, it asks what must be recorded when those phenomena determine a magnetic result.

Table 2. Minimum suspension-state record

Variable	Minimum record	Why it matters for magnetic qualification	Prohibited shortcut
Loading	Mass or volume basis and magnetic phase identity	Governs nominal magnetic fraction	Do not infer local printed loading from nominal loading alone
Mixing history	Method, duration and sequence sufficient to reconstruct preparation	Sets the starting dispersion state	Do not label a suspension homogeneous without evidence
Time to exposure	Delay between mixing/redistribution and cure	Sedimentation can change local concentration	Do not assume the first and last layers see the same suspension
Circulation or agitation	Mode, timing and relation to exposure	Can alter settling and spatial uniformity	Do not transfer one circulation strategy universally
Applied magnetic field before cure	Field type, direction, waveform/frequency where relevant, timing	Can redistribute or align particles	Do not treat field exposure as a neutral mixing step
Spatial sampling	Location and method where used	Supports a claim of filler homogeneity	Do not use one bulk measurement to prove local uniformity

The purpose of this record is not to impose one dispersion protocol. It is to prevent the magnetic state from being separated from the suspension history that produced it.

5. Magnetic fillers couple to optical energy delivery and cure

Magnetic particles can perturb the optical conditions required for vat photopolymerisation. The direct sources describe photon interference, filler-dependent cure behaviour and printing-window changes [1-4]. This coupling belongs in ER-87 only insofar as it changes the magnetic material state; the generic physics of absorption, scattering and cure-depth control remains within ER-44.

For a magnetic-composite qualification record, the optical/cure layer should therefore identify the printer wavelength or spectral band, relevant exposure condition, filler-dependent attenuation or scattering evidence where available, cure-depth or equivalent print-window measure, and a declared polymerisation endpoint such as conversion or another justified cure metric.

The crucial restriction is that no universal exposure multiplier follows from the presence of magnetic filler. Different phases, particle sizes, concentrations and matrices can alter energy delivery differently.

Table 3. Optical-cure and printed-state coupling

	Minimum evidence	Permitted conclusion	Not established
Optical interaction	Declared wavelength/exposure plus filler-dependent attenuation, scattering or print-window evidence where relevant	The selected process accounts for the tested filled system	A universal exposure rule for magnetic fillers
Cure response	Cure depth, conversion, gel endpoint or other justified cure metric	The tested state reached the declared polymerisation endpoint	Final magnetic performance
Feature fidelity	Geometry/feature error under the tested conditions	The filled system reproduced the tested geometry within a declared window	Magnetic homogeneity
Printed density/void state	Density, porosity or equivalent structural evidence where relevant	Magnetic measurements can be tied to the realised solid state	Particle orientation or magnetisation history
Particle orientation	Orientation evidence when anisotropy is claimed	Directional microstructure is documented	A universal anisotropy magnitude

6. Printed microstructure and orientation affect magnetic anisotropy

The printed part is not defined only by its external CAD geometry. Particle distribution, voids, density gradients and orientation can change the realised magnetic response. This is especially important when magnetic fields are applied during processing to create directional structures.

Li et al. connect hard-magnetic suspension processing with printed feature fidelity, remanence and magnetisation programming [4]. The Sun research line explicitly targets particle dispersion and alignment before curing [6,9]. Okoruwa et al. provide a distinct soft-magnetic composite case in which printed material state and VSM response are linked [2].

When anisotropy is discussed, ER-87 therefore requires the direction of the printed specimen, the relevant particle-orientation state, the direction of magnetic measurement and the magnetisation field history to be reported together. An isotropic material assumption is not permitted merely because the base resin is isotropic.

7. Magnetisation history is part of material identity

A hard-magnetic composite can be printed first and magnetised later, aligned during printing, or exposed to a field at multiple stages. These routes do not create equivalent magnetic states.

The minimum magnetisation record should include, as applicable:

- whether field exposure occurred before, during or after cure;
- field direction relative to the printed geometry;
- field magnitude;
- duration;
- waveform or rotational frequency where relevant;

- temperature;
- fixture or mechanical constraint;
- number and sequence of magnetisation steps;
- whether the material was already magnetised before the final programming step.

Li et al. demonstrate that magnetisation programming is integral to a hard-magnetic DLP actuator state [4]. Sun et al. use dynamic fields during the printing workflow to control particle alignment before cure [9], while the later same-lab paper focuses more narrowly on rotating-field frequency optimisation [6].

The engineering implication is simple: **magnetisation protocol is part of the specimen state, not a detachable test accessory.**

8. Direct magnetic measurement is required

Functional behaviour should not be inferred from filler loading, filler identity or a successful actuation demonstration. Direct magnetic metrics are required when the paper makes a magnetic-property claim.

The relevant metric depends on magnetic class and purpose. Soft-magnetic materials may require permeability, coercivity, hysteresis or loss-related measurements under appropriate conditions. Hard-magnetic materials may require remanence, coercivity and demagnetisation behaviour. VSM measurements can be useful for small printed specimens, but specimen geometry, field range, anisotropy and demagnetising effects must still be addressed.

Okoruwa et al. use direct VSM measurements in a soft-magnetic VPP composite [2]. Li et al. report remanence in a hard-magnetic DLP system [4]. The Sun papers link field-assisted alignment to direct magnetic response, again with the caveat that they belong to one evidence family [6,9].

Table 4. Selecting a magnetic measurement without overclaiming

Magnetic question	Candidate metric or method class	Required state information	What the metric cannot establish alone
Soft-magnetic response	M-H loop, coercivity, permeability or related d.c./a.c. property	Magnetic class, geometry, orientation, field range, circuit configuration	Actuation or service retention
Hard-magnetic state	Remanence, coercivity, demagnetisation curve	Magnetisation history, geometry, direction and demagnetising treatment	Printed homogeneity
Alignment effect	Direction-resolved magnetic response plus structural/orientation evidence	Field history and measurement direction	Independent confirmation if sources share the same method lineage
Field-responsive function	Direct response under declared external field	Field magnitude/direction/waveform, geometry, temperature, constraints	Intrinsic magnetic property without direct magnetic measurement
Retained function	Repeated magnetic metrics plus dimensional/mechanical state	Ageing/cycling history and same measurement basis	Universal service life

9. Functional response is condition-bounded

Magnetic composites can be used to generate movement, force, torque, reconfiguration, heating or other responses. Such results are meaningful only under the field and mechanical conditions that produced them.

Zhou et al. demonstrate magnetic manipulation in a specific soft-millirobot implementation [1]. Rossegger et al. demonstrate magnetically driven movement in Fe₃O₄-filled thiol-click structures [3]. Li et al. couple hard-magnetic material design with actuator behaviour [4]. Peng et al. provide a bounded magnetic shape-memory example [5]. The Sun research line demonstrates complex field-programmed response in hard-magnetic DLP systems [6,9].

ER-87 therefore requires a functional test to record field strength, direction, spatial configuration, waveform/frequency where relevant, specimen geometry, temperature and mechanical constraints. A force or displacement value should not be transferred to a different geometry or field condition without a justified model or new measurement.

10. Soft- and hard-magnetic systems should not be pooled without state reconciliation

The controlled source set intentionally spans different magnetic classes because the qualification architecture must accommodate them. That breadth does not justify numerical pooling.

A soft-magnetic Fe-Si composite characterised for magnetic response [2] is not equivalent to a hard-magnetic particle system designed to retain a programmed magnetisation [4,6,9]. Likewise, Fe₃O₄-filled soft magnetoactive photopolymers [3] serve a different material and functional logic from a hard-magnetic remanent actuator.

Cross-study comparison therefore requires at least:

1. the same or explicitly reconciled magnetic class;
2. comparable filler-state description;
3. comparable printed microstructure and orientation;
4. comparable magnetisation history;
5. compatible magnetic measurement method and geometry;
6. compatible normalization and field units;
7. declared functional-test conditions if function is compared.

Without those conditions, qualitative comparison is preferable to ranking.

11. Dynamic-field evidence: M09 and M06 are one evidence family

The source gate identified a specific independence problem in the two 2026 field-assisted DLP papers from the Zhejiang University research line [6,9]. All seven authors of M06 are also authors of M09, and both papers address time-varying or rotating magnetic-field-assisted DLP for hard-magnetic particle dispersion and alignment.

ER-87 therefore applies a conservative evidence rule:

- M09 is the primary architecture source for dynamic-field dispersion, alignment, remanence and fabrication reliability [9].
- M06 is used only for the narrower rotating-field frequency-optimisation and dual-indicator extension [6].
- The two papers are never counted as independent corroboration.

Table 5. Evidence weighting for the same-lab dynamic-field papers

Source	Role in ER-87	Permitted use	Not permitted
M09, Advanced Materials 2026	Primary architecture source	Dynamic-field control of aggregation/alignment, remanence and fabrication reliability	Count as independent confirmation of M06
M06, Materials Science and Engineering: B 2026	Narrower optimisation extension	Rotating-field frequency, dispersion/alignment evaluation and source-bounded functional demonstration	Count as an independent laboratory or duplicate the architecture claim
Combined family	One methodological lineage	Support a mechanistically coherent same-lab progression	Inflate evidence strength by treating two publications as two independent replications

This rule is important because publication count is not the same as evidentiary independence.

12. Magnetic shape-memory is a bounded application branch

Peng et al. demonstrate a DLP-printable magnetic shape-memory composite that combines magnetic responsiveness with shape-memory behaviour [5]. This is relevant to ER-87 because it illustrates that the magnetic state can be coupled to another functional material state.

However, shape fixity, shape recovery, thermal programming and generic 4D design belong to the neighbouring shape-memory/4D literature. ER-87 therefore uses M05 only to support the principle that a magnetic function must be reported together with the material and field conditions that activate it.

No biomedical suitability, universal shape-memory performance or general soft-robotics conclusion is transferred from this branch.

13. Magnetic hyperthermia is application-specific and does not define polymer-composite qualification

Luo et al. report a vat-photopolymerisation-enabled HA/MgFe₂O₄ bioceramic scaffold with magnetic-hyperthermia and osteogenic endpoints [7]. The source is useful only as a bounded demonstration that a magnetic response can be highly application-specific and coupled to a ceramic processing route.

ER-87 does not transfer hyperthermia behaviour from this scaffold to polymer composites. It does not infer implant suitability, biological safety, clinical effectiveness or a universal alternating-field condition. Those questions remain outside scope and, where relevant, belong to the biological/implant/sterilisation corpus boundaries.

The appropriate lesson is methodological: **a functional magnetic endpoint is valid only for the tested material state and declared field condition.**

14. Post-pyrolysis electromagnetic-loss ceramics are context only

Mao et al. use vat photopolymerisation as a shaping route for a precursor that is subsequently converted to a SiCN(Ni) ceramic with electromagnetic-wave absorption behaviour [8]. This study is not direct evidence for the magnetic response of a cured photopolymer composite.

Its only role in ER-87 is to reinforce a material-state boundary: a post-pyrolysis ceramic is a different material from its VPP precursor. Magnetic-loss or electromagnetic-absorption performance measured after pyrolysis must not be transferred backwards to the uncured or cured polymer composite.

The detailed qualification of electromagnetic absorption belongs primarily to ER-16/ER-19 and related electrical/electromagnetic work.

15. Retained magnetic performance is an explicit source gap

The controlled direct-source set supports filler-state, cure-coupling, alignment, magnetisation and condition-bounded functional claims. It does not support a universal service-life statement for magnetically functional VPP composites.

ER-87 therefore keeps C08 OPEN BY DESIGN.

A retained-performance programme should, as relevant, measure:

- repeat magnetic metrics after cycling or ageing;
- dimensional stability;
- mechanical damage or modulus/strength change where function depends on mechanics;
- particle migration or redistribution where plausible;
- repeated functional response under the same declared field condition;
- changes in geometry, orientation or magnetisation state;
- environmental exposure history.

A single successful actuation, remanence measurement or short-duration demonstration cannot be converted into a service-life claim.

16. Minimum qualification architecture

The qualification chain should connect each state to the next rather than treating magnetic testing as an isolated final step.

Table 6. Minimum qualification architecture for magnetically functional VPP composites

Domain	Minimum record or measurement	Required conclusion	Not established by that record alone
Magnetic phase	Chemistry/phase, particle size, density, surface treatment, loading, batch	The magnetic phase is identified and reproducible	Printed magnetic state

Domain	Minimum record or measurement	Required conclusion	Not established by that record alone
Suspension	Mixing, settling/circulation, field exposure and spatial homogeneity evidence	Uncontrolled filler gradients are bounded	Cure fidelity or magnetic performance
Optical/cure	Spectrum/exposure, filler-dependent print-window evidence, cure depth or conversion/gel endpoint	The filler did not invalidate the declared print process	Final magnetic properties
Printed state	Density/voids, particle orientation, microstructure, geometry/feature error, anisotropy	Magnetic measurements can be tied to the realised part	Magnetisation history
Magnetisation	Timing, field, direction, duration, waveform/frequency, temperature, fixture	The magnetic state is defined rather than assumed	Direct magnetic metrics
Direct magnetic test	Valid method/geometry and M-H, remanence, coercivity, permeability or related metric as applicable	Magnetic response is measured directly	Actuation or service performance
Functional test	Field conditions, geometry, temperature, constraints and response metric	Function is condition-bounded	Long-term retention
Retention	Cycling/ageing history plus repeated magnetic, dimensional and mechanical measures	Performance remains within a declared test window	Transfer to another resin/process or universal service life

The architecture is modular. Not every application needs every possible magnetic metric, but every claimed conclusion must have the state information required to support it.

17. Cross-study comparison gate

A numerical comparison between magnetic VPP studies is defensible only when the underlying states are compatible or can be reconciled.

ER-87 proposes four comparison levels:

1. **Matched state:** same magnetic class, comparable filler and suspension state, comparable printed orientation, comparable magnetisation history and compatible magnetic test method. Quantitative comparison may be defensible.
2. **Reconciled state:** differences exist but are explicitly convertible or modelled with adequate metadata and uncertainty. Quantitative comparison may be possible with caveats.
3. **Stratified state:** important differences in magnetic class, processing, geometry or measurement remain. Compare qualitatively or within subgroups.
4. **Unresolved state:** one or more essential states are missing. Numerical ranking is not defensible.

This gate prevents an apparently simple metric such as remanence or displacement from being detached from the process and geometry that created it.

18. Standards boundary: adjacent magnetic methods, not a VPP acceptance standard

IEC 60404 and ASTM magnetic test standards provide established methods for selected magnetic classes and specimen configurations [S1-S8]. They are valuable inputs to direct magnetic measurement but do not validate the whole VPP composite workflow.

Table 7. Adjacent standards and their ER-87 boundary

Standard	Relevant role	ER-87 boundary
IEC 60404-4	D.c. properties of magnetically soft materials	Adjacent method only; specimen/circuit assumptions must be met

Standard	Relevant role	ER-87 boundary
IEC 60404-5	Permanent magnet material measurements	Adjacent method only; does not validate VPP processing or actuation
IEC 60404-6:2018+A1:2021	A.c. properties of soft metallic, powder and composite materials using ring specimens	Ring-specimen transfer to printed geometry must be justified
IEC 60404-18:2025	Open-circuit permanent-magnet measurement using SCM-VSM or extraction methods	Homogeneity and demagnetising assumptions must be justified
ASTM A341/A341M-16(2022)	D.c. soft-magnetic measurements	Adjacent method only
ASTM A596/A596M-21	D.c. magnetic properties using ring specimens	Geometry-specific; not a printed-composite qualification standard
ASTM A773/A773M-21	D.c. measurements of low-coercivity materials	Magnetic-class limitations apply
ASTM A977/A977M-07(2020)	High-coercivity permanent-magnet measurements	Does not validate field-programmed VPP function or retention

No published IEC, ISO or ASTM standard was identified in the controlled gate that directly governs the complete chain from filled VPP suspension through cure, magnetisation, direct magnetic measurement, functional response and retention. ER-87 therefore does not create an ersatz standard. It defines reporting and qualification questions around the methods that already exist.

The maintenance or stability dates of individual IEC documents are deliberately not used as scientific claims in this manuscript. Their status was refreshed against the IEC Webstore on 26 August 2026 (IEC 60404-4: stability date 2028; IEC 60404-6: stability date 2029).

19. Manufacturer implementation context: 3Dresyn MB1

The 3Dresyn MB1 Magnetic Black product page is included only as first-party implementation context [M1]. The controlled manufacturer record describes a magnetite-filled photopolymer that is attracted by external magnets and is not a permanent magnet.

ER-87 does not use that page to claim saturation magnetisation, remanence, coercivity, susceptibility, actuation, field programming, hyperthermia, biological suitability or long-term performance. No magnetic performance is inferred from the product name, colour or filler identity.

Any future product-specific magnetic statement would require the exact resin version, printer/process state, mixing history, specimen geometry, post-cure, magnetic test method and external-field conditions.

20. Boundaries with neighbouring ER/WP papers

ER-87 is intentionally narrow even though magnetic composites touch many neighbouring disciplines.

- **ER-36:** generic rheology, dispersion, recoating and sedimentation science remains outside ER-87. ER-87 records those variables only when they define magnetic material state.
- **ER-44:** generic absorber/scatterer optics and cure-depth physics remain outside. ER-87 uses only magnetic-filler-specific coupling to the declared print window.
- **ER-24 / ER-48 / WP-14:** generic soft robotics, shape-memory and 4D-device qualification remain outside. M05 is a bounded illustration only.
- **ER-16 / ER-19 / ER-21 / RP-01:** EMI shielding, electromagnetic absorption, electrical, piezoelectric, ferroelectric and dielectric qualification remain outside. M08 is context only.
- **ER-43 / ER-69 / ER-70:** generic interface, fatigue-crack and fracture qualification remain outside. Mechanical state enters ER-87 only when it affects magnetic function or retention.
- **ER-06 / ER-23 / ER-42:** biological response, implant, sterilisation and clinical suitability remain outside. M07 does not create a clinical or implant claim.

These boundaries are necessary to keep the paper focused on the magnetic material-state chain rather than on a catalogue of magnetically enabled applications.

21. Interpretation failures to avoid

Table 8. Common failure modes and required correction

Failure mode	Why it fails	Required correction
Infer magnetic performance from filler identity	Magnetic response depends on phase, state, distribution and test method	Measure the printed magnetic state directly
Treat nominal loading as local printed loading	Settling/agglomeration can create gradients	Record suspension history and spatial homogeneity evidence
Apply one universal exposure correction	Optical interaction depends on filler and matrix	Establish a filler-specific print window
Assume printed isotropy	Field-assisted orientation and geometry can create anisotropy	Record orientation and measurement direction
Omit magnetisation history	Hard-magnetic state depends on field history	Report timing, field, direction, duration and fixture
Infer actuation from an M-H loop alone	Functional response depends on field and mechanical constraints	Perform a declared functional test
Compare soft- and hard-magnetic metrics directly	Magnetic classes and methods differ	Reconcile class, geometry and method first
Count M06 and M09 as independent replication	They share the same laboratory and method lineage	Treat as one evidence family
Transfer hyperthermia or EM-loss results across material states	Ceramic/application endpoints are state-specific	Keep M07 bounded and M08 context-only
Claim service life from one demonstration	Long-term retention evidence is absent	Keep C08 open and perform dedicated cycling/ageing qualification
Treat an adjacent IEC/ASTM method as a VPP standard	It validates only a defined magnetic measurement	Preserve specimen/class/method boundaries
Treat manufacturer context as independent performance evidence	First-party product description is not independent validation	Require controlled product-specific measurements

22. Limitations

The source set is deliberately compact and heterogeneous. It supports the eight-stage qualification architecture but does not provide balanced evidence for every magnetic class or end use. Some direct papers focus on processing and actuation, others on soft-magnetic or hard-magnetic metrics. M06 and M09 originate from one research line and are therefore weighted as a single evidence family rather than as independent replication.

The retained-performance branch remains a declared evidence gap. ER-87 does not establish universal cycling, ageing, particle-migration or service-life criteria. Likewise, the adjacent standards were selected as magnetic measurement references, not as VPP-specific qualification documents. Their current edition/status and the IEC 60404-4 / IEC 60404-6 stability dates were refreshed against the IEC Webstore on 26 August 2026; their specimen assumptions must still be checked before use.

Application-specific branches are intentionally bounded. M05 does not convert ER-87 into a generic shape-memory review. M07 does not support polymer-composite hyperthermia, implant or clinical conclusions. M08 does not transfer post-pyrolysis electromagnetic-loss behaviour to cured photopolymers. The 3Dresyn MB1 product page is first-party context only.

The review also does not disclose or recommend proprietary formulation, dispersion, stabilisation or magnetisation recipes.

23. Conclusions

Magnetic function in a vat-photopolymerised composite is a state-dependent property, not a label supplied by filler identity or a single device demonstration.

A defensible qualification chain connects:

magnetic phase and particle state

- **dispersion, agglomeration and sedimentation state**
- **optical-cure coupling**
- **printed microstructure, orientation and anisotropy**
- **magnetisation timing and field history**
- **direct magnetic metrics**
- **functional response under declared conditions**
- **retained magnetic, dimensional and mechanical performance**

The controlled literature supports the first seven links under source-specific conditions. The eighth, retained performance and service life, remains an explicit qualification gap and must not be inferred.

Direct magnetic measurements should be selected according to magnetic class, specimen geometry and method validity. Adjacent IEC and ASTM methods can support those measurements but do not constitute a VPP magnetic-composite acceptance standard. Functional results must remain tied to field conditions, geometry and mechanical constraints. Same-laboratory papers must not be double-counted as independent evidence.

The practical output of ER-87 is therefore not a universal magnetic-resin recipe. It is a reporting and comparison gate that keeps the magnetic material state reconstructable from suspension through printed part, magnetisation and test.

Declarations

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Data availability: This review uses published literature, standards metadata and first-party manufacturer information identified in the references. No new experimental dataset was generated.

References

- [1] Zhou, A.; Xu, C.; Kanitthamniyom, P.; Ng, C. S. X.; Lim, G. J.; Lew, W. S.; Vasoo, S.; Zhang, X.; Lum, G. Z.; Zhang, Y. Magnetic Soft Millirobots 3D Printed by Circulating Vat Photopolymerization to Manipulate Droplets Containing Hazardous Agents for In Vitro Diagnostics. *Advanced Materials* 2022, 34(15), e2200061. DOI: <https://doi.org/10.1002/adma.202200061>
- [2] Okoruwa, L.; Sameni, F.; Borisov, P.; Sabet, E. 3D Printing Soft Magnet: Binder Study for Vat Photopolymerization of Ferrosilicon Magnetic Composites. *Polymers* 2023, 15(16), 3482. DOI: <https://doi.org/10.3390/polym15163482>
- [3] Rossegger, E.; Höller, R.; Hrbinič, K.; Sangermano, M.; Griesser, T.; Schlögl, S. 3D Printing of Soft Magnetoactive Devices with Thiol-Click Photopolymer Composites. *Advanced Engineering Materials* 2023, 25(7), 2200749. DOI: <https://doi.org/10.1002/adem.202200749>
- [4] Li, X.; Zhang, D.; Wang, H.; Yang, R.; Yuan, H. Shape-programmable hard-magnetic soft actuators with high magnetic particle content via digital light processing method. *Composites Part A: Applied Science and Manufacturing* 2025, 188, 108554. DOI: <https://doi.org/10.1016/j.compositesa.2024.108554>
- [5] Peng, D.; Lin, Z.; Kuzhandaivel, D.; Pu, X.; Wu, L.; Weng, Z. Highly stretchable, magnetic responsive, shape memory polymer composites via digital light processing 3D printing: Synthesis, characterization and applications. *Polymer* 2025, 338, 129109. DOI: <https://doi.org/10.1016/j.polymer.2025.129109>
- [6] Sun, H.; Zhang, C.; Zhang, Y.; Tang, D.; Dai, H.; Pan, C.; Zhao, P. Enhancing magnetization alignment in 3D-printed magnetic composites via rotating magnetic fields: principle and optimization. *Materials Science and Engineering: B* 2026, 329, 119464. DOI: <https://doi.org/10.1016/j.mseb.2026.119464>

- [7] Luo, Yu; Zhang, Ren-Zhong; Wu, Jia-Min; He, Yi-Ning; Shi, Yun-Song; Li, Ze-Yuan; Liu, Zi-Mo; Shi, Yu-Sheng. Bifunctional hierarchical HA/MgFe₂O₄ bioceramic scaffolds with magnetic hyperthermia and osteogenic activity fabricated by vat photopolymerization. *Ceramics International* 2026, 52(16), 31295-31307. DOI: <https://doi.org/10.1016/j.ceramint.2026.05.196>
- [8] Mao, K.; Liu, C.; Sun, H.; Hu, Q.; Chang, Z.; Gong, H.; Zhu, H.; Colombo, P.; Feng, Y.; Guo, X. Vat photopolymerization 3D printed SiCN (Ni) ceramics possessing complete absorption of electromagnetic waves in the X-band and infrared stealth characteristics. *Ceramics International* 2026, 52(1), 525-536. DOI: <https://doi.org/10.1016/j.ceramint.2025.11.351>
- [9] Sun, H.; Zhang, C.; Hu, Z.; Huang, Y.; Zhang, Y.; Tang, D.; Dai, H.; Pan, C.; Zhao, P. Dynamic Magnetic Alignment Boosts Remanence and Fabrication Reliability in DLP Manufacturing of Magnetic Functional Materials. *Advanced Materials* 2026, 38(28), e19123. DOI: <https://doi.org/10.1002/adma.202519123>
- [S1] IEC 60404-4:1995+A1:2000+A2:2008 CSV. Magnetic materials - Part 4: Methods of measurement of d.c. magnetic properties of magnetically soft materials. International Electrotechnical Commission. <https://webstore.iec.ch/en/publication/2075>
- [S2] IEC 60404-5:2015. Magnetic materials - Part 5: Permanent magnet (magnetically hard) materials - Methods of measurement of magnetic properties. International Electrotechnical Commission. <https://webstore.iec.ch/en/publication/22142>
- [S3] IEC 60404-6:2018+A1:2021 CSV. Magnetic materials - Part 6: Methods of measurement of magnetic properties of magnetically soft metallic and powder materials at frequencies in the range 20 Hz to 100 kHz by the use of ring specimens. International Electrotechnical Commission. <https://webstore.iec.ch/en/publication/69674>
- [S4] IEC 60404-18:2025. Magnetic materials - Part 18: Methods of measurement of the magnetic properties of permanent magnet materials in an open magnetic circuit using a superconducting magnet VSM or an extraction method. International Electrotechnical Commission. <https://webstore.iec.ch/en/publication/76495>
- [S5] ASTM A341/A341M-16(2022). Standard Test Method for Direct Current Magnetic Properties of Soft Magnetic Materials Using D-C Permeameters and the Point by Point (Ballistic) Test Methods. ASTM International. https://store.astm.org/a0341_a0341m-16r22.html
- [S6] ASTM A596/A596M-21. Standard Test Method for Direct-Current Magnetic Properties of Materials Using the Ballistic Method and Ring Specimens. ASTM International. https://store.astm.org/a0596_a0596m-21.html
- [S7] ASTM A773/A773M-21. Standard Test Method for Direct Current Magnetic Properties of Low Coercivity Magnetic Materials Using Hysteresigraphs. ASTM International. https://store.astm.org/a0773_a0773m-21.html
- [S8] ASTM A977/A977M-07(2020). Standard Test Method for Magnetic Properties of High-Coercivity Permanent Magnet Materials Using Hysteresigraphs. ASTM International. https://store.astm.org/a0977_a0977m-07r20.html
- [M1] 3Dresyns by Resyner Technologies S.L. 3Dresyn MB1 Magnetic Black for direct 3D printing of black magnetite jewelry. Manufacturer implementation context only. <https://www.3dresyns.com/products/3dresyn-mb1-magnetic-black-for-direct-3d-printing-of-black-magnetite-jewelry>