International Journal of Engineering Research and Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 22, Issue 11 (November 2026), PP 13-20

CNT-Filled Polymer Feedstocks for Material-Extrusion Additive Manufacturing in Oil and Gas Applications

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Abstract
Carbon-nanotube (CNT)-filled thermoplastic filaments can combine the geometric freedom of fused filament fabrication (FFF, also termed fused deposition modeling) with electrical, sensing, electromagnetic-shielding, or selected mechanical functions. This critical review evaluates these materials' potential separately from the performance and qualification of printed components for oil-and-gas service. The literature considered includes CNT/polymer feedstock and printed-part studies, relevant work on FFF interlayer structure and test methodology, and reviews of additive manufacturing in energy-sector applications. It is treated as a narrative review rather than a systematic search. Across ABS, PLA, TPU, PBT and PEEK matrices, experimental studies demonstrate printable CNT-containing materials and application-specific functions, but reported outcomes depend on polymer, nanotube type and loading, compounding route, filament quality, print parameters and build direction. Conductivity and sensing are particularly sensitive to network structure and measurement direction; the presence of CNTs does not ensure large thermal-conductivity gains or improved strength in every system. The available evidence does not establish qualification of CNT/FFF components for mission-critical oilfield service. In particular, application-representative chemical exposure, pressure–temperature aging, creep, fatigue, network stability, manufacturing repeatability and traceability must be linked to component-level acceptance criteria. A staged validation pathway is proposed, with standards used as test scaffolds rather than proof of service suitability. The central conclusion is that CNT/FFF materials have demonstrated laboratory functionality, while field readiness remains an unproven engineering claim.

Keywords: *carbon nanotubes; polymer nanocomposites; fused filament fabrication; material extrusion; oil and gas; qualification; interlayer bonding; multifunctional materials*

Date of Submission: 27-10-2026 Date of acceptance: 06-11-2026

I. Introduction

Material-extrusion additive manufacturing offers a route to low-volume, geometrically customized polymer parts and can support distributed manufacture, repair and production of fixtures or tooling. Reviews of additive manufacturing in oil and gas describe opportunities for customization and supply-chain responsiveness while emphasizing that adoption is constrained by materials, process control, standards and qualification requirements [1–3]. These sector-level opportunities do not establish the suitability of a particular polymer formulation or printed part for a given service environment.

Carbon nanotubes (CNTs) are used in polymer composites to alter electrical transport, mechanical response, thermal transport and sensing behavior. When incorporated into thermoplastic feedstocks, they can make FFF parts electrically functional and, under selected conditions, change stiffness or strength. Reviews of CNT/polymer processing and nanomaterial-reinforced FFF filaments identify dispersion, polymer/filler pairing, processing history and CNT concentration as determinants of the resulting properties [4,5]. Those variables become coupled in FFF: compounding sets the initial CNT distribution; filament extrusion sets feedstock uniformity and dimensions; printing introduces further shear, orientation, porosity and interbead interfaces.

This review addresses a specific translational gap: evidence that CNT-filled polymer can be compounded and printed with a measurable laboratory function is not equivalent to evidence that a printed component is reliable in oilfield service. The distinction matters because an oilfield component may experience combinations of sustained load, cycling, elevated temperature, pressure, water, brine, hydrocarbons, carbon dioxide or sour media, while also requiring dimensional stability, electrical reliability, traceability and controlled failure modes. The literature reviewed below supports the feasibility of functional CNT/FFF material systems, but it does not by itself demonstrate qualification of such components for mission-critical duty.

The review therefore synthesizes process–structure–property evidence, evaluates the limits of reported mechanical and multifunctional outcomes, and proposes a staged validation framework. The emphasis is not on a single universal CNT formulation. Rather, the central question is whether a material, process window and component geometry can be jointly qualified for a defined service envelope.

II. Literature Review

This is a narrative critical review, not a systematic review or meta-analysis. It draws on verified scholarly records and abstracts for studies directly addressing CNT-containing polymer feedstocks or printed CNT/polymer parts, alongside selected research on FFF interlayer bonding, mechanical testing, creep and oil-and-gas additive manufacturing. The core evidence comprises experimental CNT/FFF systems in ABS, PLA, TPU, PBT and PEEK; broader nanomaterial or polymer-AM sources are used only to frame mechanisms or methods. No claim of exhaustive database coverage is made.

Evidence is classified by proximity to the application question: (i) direct CNT/polymer material-extrusion studies; (ii) adjacent FFF evidence on layer bonding, anisotropy, testing or time-dependent behavior; and (iii) sector-level oil-and-gas AM reviews. A result from one class is not treated as evidence for another. For example, a CNT/TPU pressure-sensing demonstration is evidence of a functional laboratory sensor layer, not of pressure-sensor durability in a downhole environment. Similarly, an FFF PEEK study informs compounding and feedstock issues but cannot qualify CNT/FFF parts in oilfield media. Numerical outcomes are reported only when explicitly available in the verified study record and are tied to the material, process, and test conditions.

III. CNTs in thermoplastic feedstocks

3.1. Dispersion, interfaces and morphology

CNTs have high aspect ratios and can form mechanically or electrically connected structures at comparatively modest filler contents, but the response of a polymer composite depends on the structure actually produced, not on nanotube properties in isolation. Bundles, agglomerates, tube breakage, surface chemistry, aspect-ratio distribution, and polymer wetting all influence stress transfer and network connectivity [4,5]. Polymer functionalization can improve compatibility or dispersibility, but modification changes the nanotube surface and may also affect conductivity, processing, and cost; it should be evaluated as a formulation variable rather than assumed to be beneficial [6].

The available mixing evidence cautions against universal claims about a preferred dispersion route. In TPU, Sui et al. found that the relative performance of solution and melt mixing depended on CNT loading and whether the nanotubes were pristine or carboxyl-functionalized [7]. That result is matrix- and preparation-specific, but it illustrates the broader point: a mixing method cannot be ranked independently of formulation and target property. Solution processing can aid debundling but introduces solvent handling and removal steps; melt compounding is compatible with thermoplastic processing but must balance distributive mixing against the possibility of damaging nanotube length or degrading the polymer. The relevant outcome is a measurable, reproducible distribution in feedstock and printed parts, not a visually persuasive micrograph from a small field of view.

Functionalization and interfacial engineering are therefore trade-offs. Better interfacial interaction may improve stress transfer or stabilize dispersion, but it does not remove the need to demonstrate filament homogeneity, interlayer fusion and property retention after printing. For electrically functional materials, a formulation that improves load transfer can also alter CNT–CNT contacts and thus change conductivity. A sound study should characterize both the processing state and the targeted function, rather than use a single indicator such as microscopy to imply all relevant mechanisms.

3.2. Compounding, filament quality and processability

FFF feedstock must be dimensionally consistent, sufficiently flexible for feeding, and capable of stable melt flow through the hot end. CNT addition can modify melt rheology and melt-flow behavior; the practical printability window is consequently formulation-specific. In an ABS/MWCNT study, Le et al. reported that melt-flow index decreased as CNT content increased, while the maximum tensile-strength outcome within their tested range occurred at 2 wt% MWCNT [8]. This is a study-specific relationship, not a recommended universal loading. PEEK-based material-extrusion work likewise underscores the importance of homogeneous compounding and reliable filament quality; adding CNT increased thermal conductivity in that system, whereas tensile strength was not significantly changed relative to the neat PEEK reference [9].

For process development, nominal CNT content is insufficient. Studies should report polymer grade and conditioning, CNT type and supplier-relevant characteristics, functionalization, premixing and compounding route, screw configuration or mixing conditions, thermal history, filament diameter and ovality, feed stability, and rheological or extrusion metrics. Printing records should include nozzle and bed temperatures, speed, layer height, bead width, raster strategy, cooling, infill, build orientation and relevant machine settings. Where a concentration

series is studied, neat polymer and filled feedstocks should each be process-optimized under declared rules; otherwise, a measured difference may conflate composition with a poor or unequal print window.

The step from a laboratory filament to a reproducible feedstock batch is itself a scale-up problem. Diameter variation, CNT-rich zones, moisture, pellet-to-filament thermal history and spool-to-spool differences can affect feeding and deposited bead geometry. A production-relevant specification should link tolerances in feedstock properties to measurable print outcomes. Until this relationship is characterized, a reported optimum in a small batch is best understood as a local process result, not an established material specification.

IV. Direct evidence from CNT-containing FFF systems

Experimental studies show that CNT-containing thermoplastics can be made into FFF filaments and printed into specimens with altered mechanical and electrical behavior. However, effects differ across polymer matrices and study conditions, and several papers explicitly investigate multifunctional performance rather than oilfield qualification. Table 1 summarizes representative, directly relevant examples without treating their outcomes as directly rankable. Values and observations are confined to the systems and conditions identified by each study.

Table 1. Representative direct evidence for CNT-containing material-extrusion systems

System and route	Reported study outcome	Interpretive boundary
ABS/MWCNT; melt compounded and FFF printed	Tensile modulus and strength increased; elongation at break decreased. Printed parts remained conductive, but less conductive than the composite filament.	The 6 wt% formulation was identified as optimal for FDM in this study; the result is not transferable as a general ABS/CNT target. [10]
ABS/CNT; multiple CNT fractions	CNT content significantly affected mechanical response and conductivity; the study reported a 12.6% tensile-strength improvement for printed samples at high CNT content.	Loading and electrical response were nonlinear; the reported value belongs to the tested ABS feedstock and print/test setup. [11]
ABS/MWCNT; single-screw-extruded filament	Within the tested 0.5–4 wt% range, 2 wt% gave the highest reported tensile strength, 44.57 MPa, 42% above the neat ABS sample. MFI fell as CNT content rose.	A study-specific concentration optimum; printability and tensile result must be interpreted with its single-screw compounding route and specimen protocol. [8]
ABS/MWCNT; functionalized and unfunctionalized FFF parts	Across tested concentrations and two build orientations, the study identified 0.5% as best within its conditions; voids, interlayer bonding and agglomeration affected properties.	Functionalization and orientation altered outcomes; the abstract does not support a blanket improvement across all conditions. [12]
PLA/CNT; FDM printed parts	CNT content influenced thermal, mechanical and electrical properties. At 6 wt%, reported tensile and flexural strengths increased by 64.12% and 29.29%, respectively; resistivity also varied with loading and print settings.	Large relative changes are study-specific and do not establish aging, durability or strength retention in service environments. [13]
PEEK/CNT; material-extrusion composite	CNT addition increased thermal conductivity; tensile strength was not significantly changed relative to neat PEEK in the reported comparison.	High-performance matrix evidence supports the importance of compounding and filament quality, not oilfield qualification. [9]
TPU/CNT; FDM sensor dielectric layers	The reported CNT/TPU system functioned as a flexible capacitive sensor layer, with properties dependent on CNT content and printed microstructure.	Laboratory sensor demonstration; does not establish environmental endurance or calibration stability in oilfield service. [14]
PLA/HDPE with CNT; FFF electrical characterization and modeling	The study reported percolation thresholds of 0.23 vol% for CNT/PLA and 0.18 vol% for CNT/HDPE in its tested systems.	Thresholds are formulation- and process-specific, not universal CNT/polymer values. [15]

V. Mechanical response, anisotropy and failure modes

Mechanical reinforcement should be evaluated as a response vector rather than reduced to a single modulus or tensile-strength value. Stiffness, ultimate strength, strain at break, toughness, fatigue resistance, creep, and interlayer fracture can respond differently to the same CNT addition. For example, the ABS/CNT work of Dul et al. reported higher tensile modulus and strength accompanied by lower elongation at break [10]. The result illustrates a familiar trade-off: an increase in stiffness can coexist with reduced deformation capacity. It does not establish that all CNT-filled thermoplastics become more brittle, but it argues against claiming general mechanical benefit from modulus alone.

CNT distribution can also produce local stress concentrations or alter polymer mobility. A well-dispersed, suitably bonded network may contribute to load transfer, whereas bundles or voids can initiate damage. Functionalization studies in printed ABS show that morphology, voids and interlayer bonding remain relevant even when nanoparticle surface treatment is varied [12]. Claims about reinforcement mechanisms therefore require convergence among mechanical tests, fracture or microstructural evidence, and process records. A tensile increase alone cannot distinguish improved interfacial load transfer from changes in crystallinity, bead geometry, porosity or specimen variability.

FFF adds mesoscale structure to this interpretation. Raster direction, deposited-bead geometry, layer interfaces, voids and thermal history determine how load is carried through the part. Reviews describe anisotropy as a feature of additively manufactured polymers and composites, but the magnitude and mechanism are material- and test-dependent [16,17]. A study of PLA specimens found bulk-material strength at the tested layer interface while strain at fracture, specific load-bearing capacity and toughness were lower in the Z-oriented specimens, associated with filament-scale geometry [18]. This result cautions against a simplistic rule that interlayer strength is invariably a fixed fraction of in-plane strength. For CNT/FFF parts, both strength and deformation/failure measures should be tested in orientations that represent the intended load path.

Comparison across studies is further complicated by specimen geometry and test practice. Existing tensile standards were developed for conventional plastics and do not encode all print variables that govern FFF response. A literature survey and case study on FFF tensile testing recommends caution when applying existing standards, full reporting of printing and test conditions, and avoidance of arbitrary specimen-size changes [19]. Accordingly, ASTM tensile or flexural procedures may offer useful scaffolds, but they should not be presented as inherently validating an additively manufactured anisotropic material. A robust report needs specimen orientation, geometry, build and conditioning details, number of replicates, dispersion of results and failure location, alongside mean values.

VI. Electrical, sensing, electromagnetic and thermal functions

6.1. Electrical percolation and conductive function

CNT networks can enable conductive FFF parts, but threshold values depend on matrix, nanotube morphology, dispersion, processing and measurement direction. In FFF CNT/PLA and CNT/HDPE, Mora et al. reported percolation thresholds of 0.23 and 0.18 vol%, respectively, within their systems and modeling framework [15]. ABS/CNT printed elements have also shown conductivity changes with CNT loading [11], while a PLA/CNT study reported large resistivity variation across its tested loading and printing conditions [13]. These examples support the feasibility of electrically functional printed materials, not a universal threshold or a guaranteed conductivity at a given weight fraction.

Electrical performance must be reported with measurement geometry, electrode arrangement, conditioning, direction relative to rasters and layers, voltage or current regime, and uncertainty. Network continuity may be affected by bead boundaries, voids and mechanical damage. A conductivity measured on a filament cannot be substituted for the conductivity of a printed component: Dul et al. reported lower conductivity in printed ABS/CNT specimens than in the corresponding composite filament [10]. This difference is directly relevant to feedstock-to-part translation and to component design where current paths cross deposited roads or layers.

6.2. Sensing and electromagnetic shielding

Piezoresistive sensing provides an example of a function that depends on both network structure and print architecture. CNT-doped polypropylene random copolymer (PPR) feedstocks have been used to make self-sensing FFF structures, with reported strain and damage sensing behavior in laboratory specimens [20]. ABS/CNT printed sensors have shown raster-orientation-dependent piezoresistive response, and resistance changes were used to detect permanent damage during creep and fatigue experiments [21]. These results establish research pathways for health monitoring, but sensor calibration, drift, repeatability, electrical contact stability and false-positive/false-negative behavior must be examined before sensing can be credited as a safety function.

Electromagnetic-interference shielding is another application-specific possibility. FFF ABS composites containing CNT and other carbonaceous fillers showed direction-dependent conductivity, shielding effectiveness and mechanical behavior [22]. A PPR/MWCNT study likewise reported shielding performance that depended on printing direction and part architecture [23]. Such studies support the principle that formulation and toolpath can be co-designed for a functional response. They do not show that a shield retains performance after chemical exposure, thermal cycling, abrasion, pressure, cyclic deformation or field installation.

6.3. Thermal transport

The high intrinsic thermal conductivity of CNTs does not guarantee a large gain in a polymer composite. Interfacial thermal resistance at CNT–polymer and CNT–CNT contacts can limit heat transport, and the resulting

property depends on network structure and processing [24]. In a PEEK-based material-extrusion study, CNT addition increased thermal conductivity, while tensile strength did not change significantly compared with neat PEEK [9]. This is useful evidence of a possible thermal-function trade-off in one system, not evidence that CNT addition generally makes printed polymers suitable for heat-management service. Thermal diffusivity or conductivity should be measured on the printed geometry and direction relevant to the intended application, together with dimensional stability and mechanical retention after thermal exposure.

VII. Relevance to oil-and-gas service

Oil-and-gas additive manufacturing reviews describe the sector's interest in customized components, repair, tooling and supply-chain resilience, while emphasizing the need for materials and processes that can meet regulated service expectations [1–3]. A separate review of high-performance polymer AM discusses potential sector uses and associated challenges [2]. These sources frame the broader industrial context; they do not establish qualification of CNT-filled FFF parts. The material evidence summarized here is predominantly laboratory-scale and generally concerns processability, mechanical coupons, electrical function or sensor concepts rather than a component validated against an oilfield service envelope.

Service suitability is not a generic material property. The exposure question must specify the actual medium, concentration, temperature, pressure, duration, cycling, mechanical load, geometry and failure consequence. Chemical resistance results depend on matching the intended exposure conditions; ASTM D543 itself cautions that short exposure tests do not establish suitability for continuous service [25]. For printed CNT composites, chemical conditioning should be followed by assessment of mass or dimensional change, mechanical retention, interlayer damage and electrical or sensing stability where relevant. The test should also account for fluid access through voids, bead boundaries, machined surfaces and interfaces.

Time-dependent behavior is also a qualification concern. Adjacent FFF literature on PEI and PETG has characterized creep or viscoelastic response, but these studies are not CNT-specific and cannot be treated as evidence of CNT/FFF oilfield endurance [26,27]. This adjacent evidence supports inclusion of creep and recovery in a qualification program, especially where a printed component carries sustained load at elevated temperature. Fatigue, stress relaxation, pressure cycling, thermal cycling and interactions between fluid aging and mechanical damage remain to be investigated in application-relevant CNT/polymer systems.

The available evidence therefore supports a bounded conclusion: functional CNT/FFF materials have been demonstrated, while qualification of CNT/FFF components for mission-critical oilfield service is not established by the studies reviewed here. This is an evidence statement, not proof that no such work exists anywhere. It distinguishes material feasibility from component-level evidence and avoids converting the absence of qualification results in the cited evidence base into a universal claim about all research or proprietary testing.

VIII. A staged validation pathway

A credible qualification program should begin with a defined component and service case, then connect feedstock controls to process qualification, material characterization, environmental durability and component demonstration. The stages below are intended as a practical research framework; they are not a substitute for applicable operator, regulatory or product-specific requirements.

Table 2. Proposed staged validation pathway for CNT/FFF components

Stage	Minimum evidence to generate	Decision focus
1. Define service and failure consequence	Specify function, geometry, load path, pressure/temperature envelope, media, duration, duty cycle, electrical function and failure consequence.	A documented design basis and measurable acceptance criteria, including whether the part is safety-critical.
2. Qualify feedstock and process window	Record polymer grade and conditioning, CNT specification, mixing/functionalization, thermal history, filament dimensions, batch variation and extrusion/rheology indicators. Print neat and filled controls with declared, comparable optimization rules.	Repeatable feedstock and stable deposition over a defined process window; traceability from batch to specimen.
3. Establish structure–property baseline	Measure CNT distribution and agglomerates statistically; quantify porosity/voids and bead geometry where practicable. Test mechanical, electrical and thermal properties in relevant build orientations.	A reproducible baseline with uncertainty, failure modes and evidence linking structure to the target property.
4. Conduct application-relevant aging	Expose specimens to specified fluids, temperature, pressure and cycling, alone and in justified combinations. Include controls and time points; assess mass/dimensions, mechanical retention, interlayer damage and functional-network stability.	Retention criteria linked to service conditions and a documented account of degradation or irreversible changes.
5. Test component and manufacturing repeatability	Evaluate representative geometry, joints, surface finish, tolerances, post-processing, inspection and part-to-part/batch variability. Verify electrical or sensing function under load if claimed.	Component-level evidence across repeat builds, with inspection and acceptance logic suitable for production control.
6. Review qualification and lifecycle controls	Map evidence to applicable codes, operator requirements, quality system, repair/replacement strategy, CNT handling controls and end-of-life route.	A bounded decision for the named use case, plus controls for change management and continued monitoring.

8.1. Test standards as scaffolds, not qualification

ASTM D638 and D790 can inform tensile and flexural coupon testing [28,29], while ASTM D543 provides a framework for resistance to chemical reagents [25]. Their use should be accompanied by explicit FFF specimen orientation, raster and layer settings, dimensions, conditioning, print history and failure analysis. Because anisotropic printed structures do not necessarily behave like conventionally molded or machined plastics, a standard-method label alone does not make results transferable to a component or service environment [19]. Standards supply repeatable test concepts; acceptance criteria, exposure histories and component-level evidence must still be defined for the intended use.

At a minimum, reporting should include replicate count and variability; exact feedstock identity and batch; CNT morphology and surface treatment; compounding and extrusion conditions; filament dimensional quality; printer and slicer parameters; specimen geometry and orientation; test machine, rate and conditioning; electrical contact and measurement configuration; environmental exposure conditions; and raw or machine-readable data where feasible. Where microscopy or tomography is used, sampling locations and image-analysis methods should be stated. These details make the evidence more reproducible and allow reviewers to distinguish material effects from process and specimen effects.

IX. Research priorities and responsible development

The next phase of work should prioritize reproducibility and decision-relevant evidence over isolated property maxima. First, studies should compare dispersion and functionalization approaches with matched polymer, CNT batch, processing history and print settings, reporting both feedstock and printed-part properties. Second, mechanical characterization should include more than a single tensile direction: orientation-resolved strength, strain, toughness, fatigue and creep are relevant to components whose raster and layer interfaces experience different stresses. Third, electrical and sensing studies should examine calibration, drift, damage signatures and network stability after aging, not only initial conductivity or gauge response.

Fourth, environmental validation should progress from controlled screening to service-representative combinations of fluid chemistry, temperature, pressure, time and loading. The purpose is not to prescribe one universal exposure recipe, but to make the exposure traceable to a use case and to avoid interpreting a short coupon soak as evidence of continuous-service suitability. Component trials should follow only after the material and process envelope is stable enough to produce representative parts. Fifth, scale-up studies should quantify batch-to-batch filament variation, print yield, maintenance and inspection requirements, and the effects of changes in feedstock supplier or equipment.

Finally, CNT handling and lifecycle questions warrant planned assessment. Occupational exposure reviews identify CNT-containing work activities, including powder handling and some manufacturing tasks, as relevant contexts for exposure characterization and risk management [30]. This supports appropriate process-

specific exposure assessment and controls during compounding, feedstock preparation, printing, machining and cleanup; it does not justify alarmist assumptions about exposure from every finished part. Likewise, possible release during wear, machining, recycling or disposal should be measured rather than presumed. Recycling pathways should test whether CNT networks, polymer degradation or contamination alter the properties and exposure profile of reprocessed material.

X. Limitations of this review

This review is narrative and was not designed to identify every publication, patent, standard, proprietary qualification program or field deployment. The evidence summarized is restricted to verified sources cited in the reference list and is heterogeneous in polymer chemistry, CNT specification, loading, compounding, printing and test method. Consequently, cross-study rankings and pooled effect estimates would not be justified. Abstract-level summaries were used for several records; study-specific interpretation should be confirmed against complete methods and data before formulation or design decisions are made. The conclusions are therefore bounded to the evidence described, and are not a certification assessment for any named component or operator.

XI. Conclusion

CNT-filled polymer feedstocks for FFF have demonstrated laboratory-scale printability and useful electrical, sensing, EMI-shielding, mechanical or thermal responses in selected formulations. The outcomes are conditional: CNT distribution and interface, polymer matrix, loading, compounding, filament quality, print settings and build orientation all shape the printed structure and the measured function. A property gain in one formulation cannot be transferred automatically to another polymer, part geometry or load case.

For oil-and-gas translation, the decisive distinction is between material potential and component qualification. The evidence reviewed does not establish qualification of CNT/FFF components for mission-critical oilfield service. Qualification requires a defined use case and linked evidence for reproducible manufacture, orientation-sensitive mechanical behavior, time-dependent performance, exposure durability, functional stability and component-level acceptance. Standards can support repeatable testing, but do not replace application-specific exposure conditions or qualification criteria. The most defensible present position is therefore neither dismissal nor readiness: CNT/FFF is a demonstrated materials platform whose oilfield deployment claims should remain bounded until service-relevant validation is available.

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