

Additive manufacturing of silicon carbide optical mirrors and structural components

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ABSTRACT

Silicon carbide (SiC) is attractive for space optical systems because of its high specific stiffness, thermal stability, and resistance to harsh environments. For a given payload mass, its high specific stiffness enables the potential for larger apertures or lower areal-density structures, which is relevant to compact spaceborne instruments requiring high spatial resolution. However, the fabrication of SiC optical mirrors and precision structural components remains challenging when complex geometries, internal features, or integrated interfaces are required. This paper presents a process-development study for producing SiC optical components using binder jet additive manufacturing and an integrated post-processing route. A dedicated SiC binder jetting platform was developed to address material-specific challenges associated with non-spherical, poorly flowing, and abrasive SiC powders. The proposed process chain includes design, binder jet printing, curing, depowdering, densification, machining, CVD SiC coating, and optical surface preparation. Two densification routes are considered: liquid silicon infiltration (LSI) for Si-SiC components with limited dimensional change, and chemical vapor infiltration (CVI) for silicon-free porous SiC components where material purity and dimensional stability are important. CVD SiC coating is applied as a high-purity surface layer to support subsequent optical finishing. Representative printed components and mirror samples are presented to demonstrate process feasibility. Preliminary polishing results show near-nanometer-scale local RMS surface roughness on selected CVD-SiC-coated areas. The current work focuses on fabrication-route development and optical surface preparation rather than full optical qualification. Full-aperture figure measurement, wavefront error evaluation, and environmental testing remain future work.

Keywords: silicon carbide; additive manufacturing; binder jetting; optical mirrors; CVD SiC; liquid silicon infiltration; chemical vapor infiltration; space optics

1. INTRODUCTION

Silicon carbide has become an important material for high-stability optical and opto-mechanical systems. Its high elastic modulus, moderate density, high thermal conductivity, coefficient of thermal expansion lower than aluminum alloys, and environmental resistance make it attractive for telescope mirrors, mirror supports, optical benches, baffles, and precision structural components that must maintain dimensional stability under thermal and mechanical loading [1]. In space optical systems, SiC has been demonstrated as both mirror substrates and compatible SiC-based telescope structures [2,3].

For mirror substrates and structural optical components, material selection is commonly guided by basic figures of merit such as specific stiffness (E/ρ), and thermal stability index (k/α) where E is Young's modulus, ρ is density, k is thermal conductivity, and α is the coefficient of thermal expansion (CTE) [1]. These metrics do not replace full opto-mechanical analysis, but they provide a useful basis for comparing materials when payload mass, aperture, stiffness, thermal gradients, and launch loads must be balanced. For a given payload mass, a material with high specific stiffness can support a larger aperture or a lower areal-density structure while maintaining mechanical stability. This is particularly relevant to compact spaceborne instruments, where aperture is directly linked to high spatial resolution but is constrained by mass and volume.

Figure 1 summarizes the material-level trade space considered in this paper. Low-expansion glass and glass-ceramic materials such as fused silica, ULE, and Zerodur occupy an important region of this trade space because of their near-zero thermal expansion and strong heritage in optical systems. SiC occupies a different region: it combines high specific stiffness, relatively high thermal conductivity, and lower thermal expansion than aluminum alloys. Therefore, the

motivation for using SiC is not based on a single material property, but on the combined requirement for mechanical stiffness, thermal stability, structural integration, and optical surface preparation.

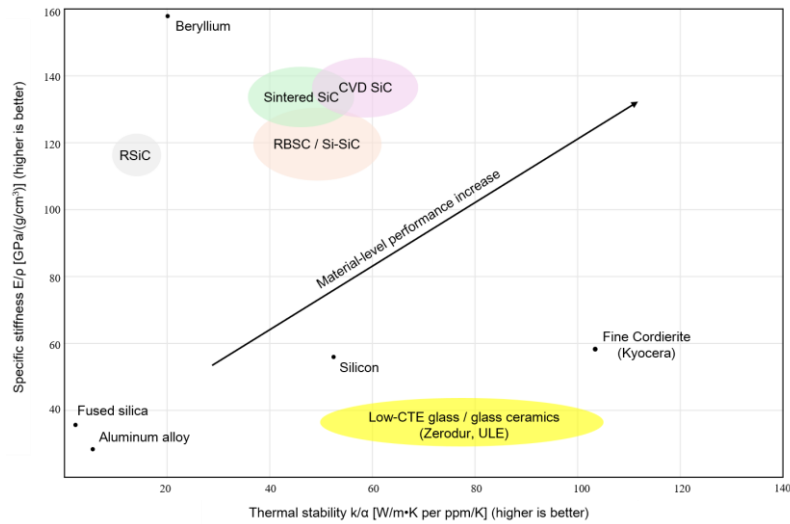


Figure 1. Representative material map for optical mirrors and structural components, comparing specific stiffness (E/ρ), and thermal stability index (k/α). Ellipses indicate representative property ranges, and points indicate mid-values. Values depend on grade, porosity, processing route, orientation, and temperature.

Aluminum alloys provide a useful comparison because they are readily machined, compatible with laser powder bed fusion (L-PBF), and suitable for single-point diamond turning (SPDT). Aluminum additive manufacturing (AM) mirrors can incorporate lattice structures and integrated mounting features, making them attractive for rapid prototyping and compact opto-mechanical assemblies. However, metal AM substrates remain sensitive to process-induced porosity, inclusions, scratch initiation, and surface defects, all of which can influence optical scatter, mechanical reliability, and surface quality [4]. The motivation of this work is therefore to transfer part of the geometric freedom of additive manufacturing to a SiC-based material system with higher stiffness and improved thermal stability.

Previous studies on additively manufactured ceramic mirrors have shown that the route from printed ceramic substrate to optical surface is non-trivial. In SiC + Si mirror samples, reflective surfaces can be produced after lapping and polishing, but the heterogeneous SiC/Si microstructure and the processing sequence before chemical vapor deposition (CVD) SiC coating can strongly influence the final optical surface [5]. In parallel, topology-optimized and double-sided AM-SiC mirror studies show that additive manufacturing can enable mirror architectures that are difficult to fabricate conventionally, such as closed-back or integrated double-sided configurations [6]. These studies also indicate that AM-SiC requires careful consideration of manufacturing feasibility, defect control, powder removal, inspectability, polishing behavior, and qualification requirements.

This work presents a fabrication route for SiC optical mirrors and structural components based on a dedicated SiC binder jetting platform. Binder jetting is attractive for SiC because the printing step does not require local melting and can form complex ceramic preforms from powder. However, SiC powders are typically angular, non-spherical, poorly flowing, and abrasive, making stable powder spreading and printer durability important process challenges. The proposed route addresses these issues by combining SiC-specific binder jet printing with curing, depowdering, densification, machining, CVD SiC coating, and optical surface preparation.

Two densification routes are considered in this paper. Liquid silicon infiltration is used for Si-SiC components when limited dimensional change and near-net-shape fabrication are important. Chemical vapor infiltration is considered for silicon-free porous SiC components where material purity and dimensional stability are important. In both cases, CVD SiC coating is treated as a functional step between the printed/densified substrate and the final optical surface, rather than as a cosmetic coating. The current level of verification is intentionally limited to process feasibility, material-property relevance, and local optical surface preparation.

Table 1. Qualitative comparison of candidate material and manufacturing routes for optical mirrors and structural components.

Route / material	Main advantages	Main limitations	Relevance to this work
Low-expansion glass / glass-ceramics	Near-zero CTE; optical heritage	Lower stiffness and thermal conductivity	Low-CTE reference
Aluminum AM mirrors	Machinable; L-PBF/SPDT compatible; integrated features	High CTE; porosity and surface defects	AM benchmark
Conventional SiC mirror blanks	High stiffness and thermal stability	Difficult machining and integration	Material baseline
Binder-jetted SiC route in this work	Geometry freedom with SiC preforms	Qualification not yet complete	Proposed process route

2. PROCESS CONCEPT

2.1 Dedicated binder jetting platform for SiC powders

The binder jetting platform used in this work was developed specifically for SiC powders rather than for spherical metal powders or highly flowable ceramic feedstocks. The objective of the printing stage is to produce stable SiC green preforms with sufficient geometric fidelity for subsequent densification, machining, CVD SiC coating, and optical surface preparation. The printed surface itself is not intended to become the final optical surface.

Binder jetting is attractive for SiC because it forms ceramic preforms without local melting, avoiding the thermal gradients and cracking risks associated with melt-based ceramic processing. However, angular, non-spherical, and abrasive SiC powders reduce flowability, complicate uniform powder spreading, and accelerate wear of powder-handling and recoating components. Therefore, stable layer deposition, controlled binder placement, powder-bed uniformity, and reliable depowdering are critical requirements for binder-jetted SiC optical components.

At the current stage, the emphasis is on demonstrating stable printing of representative optical and structural geometries using SiC powder. The printed parts are intended to validate the manufacturing route and to provide substrates for downstream densification and surface preparation.

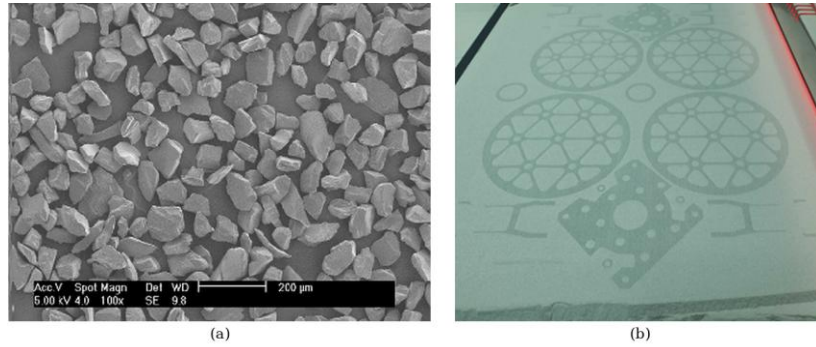


Figure 2. Morphology and printing behavior of SiC powder used for binder jetting. (a) SEM image showing angular, non-spherical SiC particles. (b) Printed layer image from the binder jetting process.

2.2 End-to-end process chain

Figure 3 summarizes the end-to-end process chain for binder-jetted SiC optical mirrors and structural components. The sequence begins with design and DfAM considerations for mirror blanks, mirror supports, baffles, or other opto-mechanical components. The design stage must consider not only the final geometry, but also powder spreading, binder penetration, depowdering, densification route, machining allowance, CVD coating allowance, and surface metrology.

After binder jet printing, the green SiC parts are cured and depowdered. The porous preforms are then densified by one of two routes. Liquid silicon infiltration is used to produce Si-SiC components with limited dimensional change, while chemical vapor infiltration is considered for silicon-free porous SiC components where material purity and dimensional stability are important. These densification routes are discussed in more detail in Section 3.

After densification, diamond-tool machining is used to refine the reference geometry and prepare the surface for coating. A CVD SiC layer is then deposited to provide a high-purity SiC surface suitable for optical finishing. The final stage is polishing and local surface metrology. In this process chain, each step has a distinct role: binder jetting defines the geometry, densification provides mechanical integrity, machining refines the geometry and coating allowance, CVD SiC coating provides the optical surface material, and polishing prepares the final local optical surface.

This process-chain view is important because the final surface quality cannot be separated from the upstream manufacturing steps. Powder spreading affects green density and local porosity; green density affects infiltration behavior; densification affects machining allowance and residual phases; machining affects CVD coating uniformity; and CVD coating quality affects polishing response. The objective of the current work is therefore not only to print SiC shapes, but to establish a manufacturing route that connects printed SiC preforms to CVD-SiC-coated and polished optical surfaces.

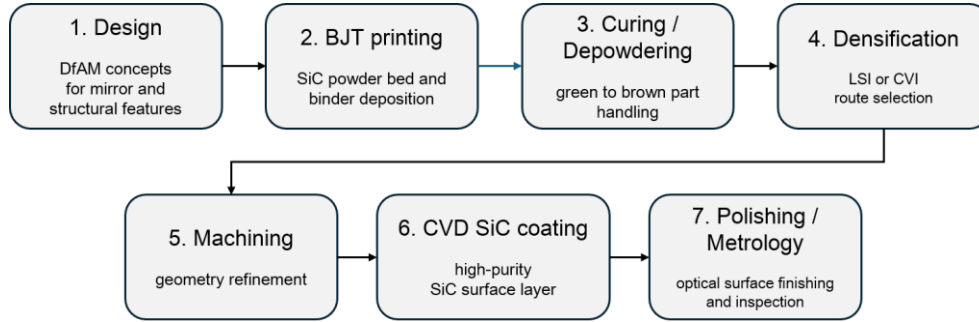


Figure 3. End-to-end process chain for binder-jetted SiC optical mirrors and structural components, including design, binder jet printing, curing and depowdering, densification, machining, CVD SiC coating, and polishing/metrology

3. DENSIFICATION AND SURFACE PREPARATION ROUTES

3.1 Liquid silicon infiltration route

Liquid silicon infiltration (LSI) is used to convert porous SiC-based preforms into Si-SiC composite components with limited dimensional change. In this route, the printed preform is prepared to contain carbonaceous phases that react with molten silicon during infiltration. The reaction forms additional SiC, while residual silicon fills the remaining pores. The resulting reaction-bonded SiC or Si-SiC composite can provide high density and dimensional stability, making it attractive for near-net-shape optical blanks and precision structural components [7].

The LSI route is especially useful when geometric fidelity is critical. Because the dimensional change during infiltration can be limited, the process is suitable for large or complex geometries where post-densification machining must be minimized. However, residual free silicon must be considered when selecting applications. For mirror substrates, residual silicon can influence thermal behavior, long-term stability, and polishing response if not properly controlled. In the present process concept, CVD SiC coating is therefore used to provide a high-purity SiC surface for optical finishing, even when the bulk component is a Si-SiC composite.

3.2 Chemical vapor infiltration route

Chemical vapor infiltration (CVI) is considered as an alternative route for producing silicon-free porous SiC components. In contrast to LSI, CVI does not rely on molten silicon infiltration and can be used when material purity, silicon-free composition, and dimensional stability of the porous preform are important. During CVI, SiC is deposited within the accessible pore network, increasing SiC content and reducing open porosity.

CVI is typically slower than LSI and may leave residual porosity depending on component thickness, gas accessibility, pore connectivity, and process time. Therefore, CVI is treated here as an application-dependent route rather than a direct replacement for LSI. The present paper does not claim complete optimization of both routes, but establishes a framework

in which binder-jetted SiC preforms can be directed toward either Si-SiC composite components or silicon-free porous SiC components depending on the application.

3.3 CVD SiC coating and optical surface preparation

CVD SiC coating is a key step for optical surface preparation. Binder-jetted and densified SiC components may contain residual porosity, local compositional variation, residual silicon, residual carbon, or machining marks that are not suitable for direct optical finishing. This is especially important for heterogeneous or porous substrates, such as Si-SiC composites produced by LSI or porous SiC substrates such as CVI-densified SiC or RSiC-type components. In these cases, the substrate itself is not a single, fully dense optical material, and substrate-related features can influence both CVD growth and polishing response.

Previous AM ceramic mirror work has shown that the transition from a printed ceramic substrate to a final optical surface is non-trivial. In SiC+Si materials, differences in polishing removal rate between SiC and Si can generate nanoscale steps at material interfaces, contributing to micro-roughness. CVD SiC coating can provide a more uniform single-material optical surface, but only when substrate preparation, coating thickness, and finishing sequence are properly controlled [5].

In the present process chain, CVD SiC coating is treated as a functional bridge between additive manufacturing and optical finishing, rather than as a simple surface coating. A high-purity CVD SiC layer is deposited on the printed and densified substrate to reduce the influence of the underlying composite microstructure and to provide a more uniform material for subsequent polishing. The CVD SiC coating thickness is typically targeted in the range of 150–300 μm to provide sufficient material allowance for grinding, lapping, and polishing while maintaining a continuous SiC surface layer after finishing.

The main optical evidence available at this stage is local surface roughness after polishing, not full-aperture figure accuracy or wavefront error. Therefore, the role of CVD SiC coating in this work is to demonstrate optical surface preparation feasibility on binder-jetted SiC-based substrates. Further work is required to evaluate coating thickness uniformity over larger apertures, residual coating thickness after polishing, full-aperture figure, wavefront error, thermal-vacuum stability, and vibration response.

Table 2. Process route comparison for binder-jetted SiC optical and structural components.

Item	LSI route	CVI route	Role of CVD SiC coating
Target component	Near-net-shape Si-SiC mirror blanks and precision components	Silicon-free porous SiC components	High-purity SiC surface layer for optical finishing
Primary advantage	Limited dimensional change and high-density composite formation	Silicon-free composition and dimensional stability	Pore sealing, surface purification, and improved polishability
Main concern	Residual free silicon and infiltration uniformity, and Si/SiC phase distribution	Long process time, gas accessibility, and residual porosity	Coating uniformity, pore bridging, substrate feature masking, and residual coating thickness after polishing
Current status in this work	Main route for representative mirror samples	Alternative route for selected porous SiC structures	Applied before polishing and roughness evaluation

4. PRELIMINARY COMPONENTS AND EVALUATION

4.1 Representative component fabrication

Representative SiC-based components were fabricated to evaluate whether the proposed process chain can be applied to optical mirror and structural-component geometries. Figure 4(a) shows an as-printed SiC structural part produced by binder jetting. This part is not a final structural component, but a printing-stage process demonstrator used to confirm that the binder jetting platform can form cylindrical walls, mounting-like features, and integrated geometries using non-spherical SiC powder.

Figure 4(b) shows a conceptual all-SiC opto-mechanical assembly targeted by the proposed process chain. The concept includes a mirror housing, mirror-back structure, optical substrate, spacer, and support interfaces. The purpose of this model is to illustrate the type of component integration that may be enabled by binder jetting, densification, machining, CVD SiC coating, and polishing. The concept model should not be interpreted as a completed or qualified optical

assembly; rather, it defines the direction for future component-level demonstrations. Together, the as-printed structural part and the concept model show the intended progression from printing-stage geometry demonstration toward integrated SiC optical and structural assemblies.

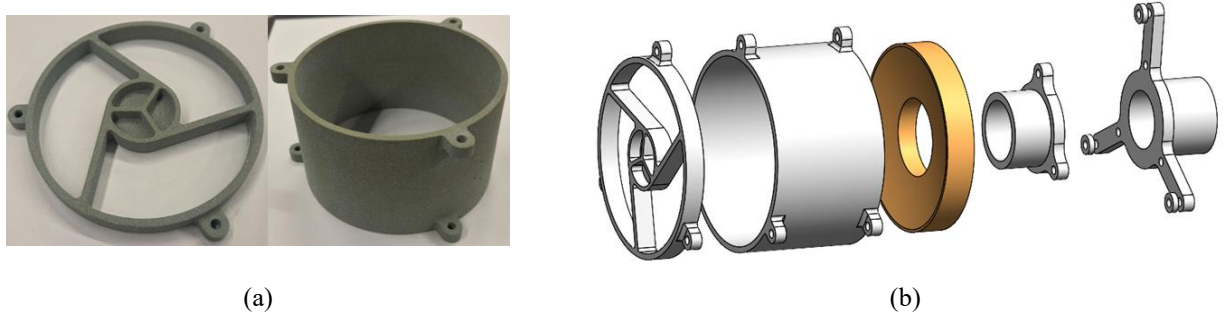


Figure 4. Representative SiC structural component and all-SiC opto-mechanical assembly concept. (a) As-printed SiC structural part produced by binder jetting. The part is a printing-stage process demonstrator and is not a final structural component. (b) Conceptual all-SiC opto-mechanical assembly showing an integrated mirror housing, mirror-back structure, optical substrate, spacer, and support interfaces.

4.2 Mechanical and thermal properties of binder-jetted RB-SiC

Mechanical and thermal properties of binder-jetted and liquid-silicon-infiltrated RB-SiC samples were compared with representative conventional RB-SiC values. The purpose of this comparison is to confirm that the binder jetting and LSI route can produce a SiC-based substrate material with properties relevant to optical and structural components.

Table 3. Representative mechanical and thermal properties of binder-jetted RB-SiC compared with conventional RB-SiC.

Property	Conventional RB-SiC	BJT AM RB-SiC
Flexural strength [MPa]	150-500	>240
Young's modulus [GPa]	270-380	>340
Thermal conductivity [W/m-K]	120-200	180
CTE [$\times 10^{-6}/K$] at 25-400 °C	3.8-4.1	3.9

4.3 CVD SiC coating and local surface preparation result

After densification and machining, CVD SiC coating was applied to provide a high-purity SiC surface layer for subsequent optical finishing. Figure 5(a) shows a representative cross-section of a CVD-SiC-coated SiC-based substrate. The coating is intended to reduce the direct influence of the underlying heterogeneous substrate, including residual silicon, residual porosity, local phase variation, and machining-induced surface damage. In the present process, the CVD SiC coating thickness is typically targeted in the range of 150–300 μm to provide sufficient allowance for grinding, lapping, and polishing while maintaining a continuous SiC surface layer after finishing.

Figure 5(b) shows a polished Si-SiC mirror and a representative mirror-back geometry after downstream processing. The polished mirror demonstrates that the process chain can progress beyond binder jet printing and densification to reflective surface preparation. The mirror-back geometry also illustrates the type of ribbed structure that can be introduced at the preform-design stage, although the sample is presented as a process demonstrator rather than a mission-specific optimized mirror structure.

Figure 5(c) shows a representative local surface metrology result of a CVD-SiC-coated and polished sample. The measurement was performed using a Zygo white-light interferometric microscope with a 10 $\times$ Mirau objective over a 1.41 mm $\times$ 1.06 mm area. The measured local RMS surface roughness was 0.999 nm, with Ra of 0.770 nm. This result indicates that approximately 1 nm-level local surface roughness can be achieved on the CVD-SiC-coated surface after polishing.

It should be noted that this measurement represents local surface roughness rather than full-aperture optical figure. Therefore, the present work does not claim full-aperture figure accuracy or wavefront error performance. Full-aperture

interferometric measurement, WFE evaluation, coating thickness uniformity over larger apertures, residual coating thickness after polishing, and environmental stability testing remain as future work.

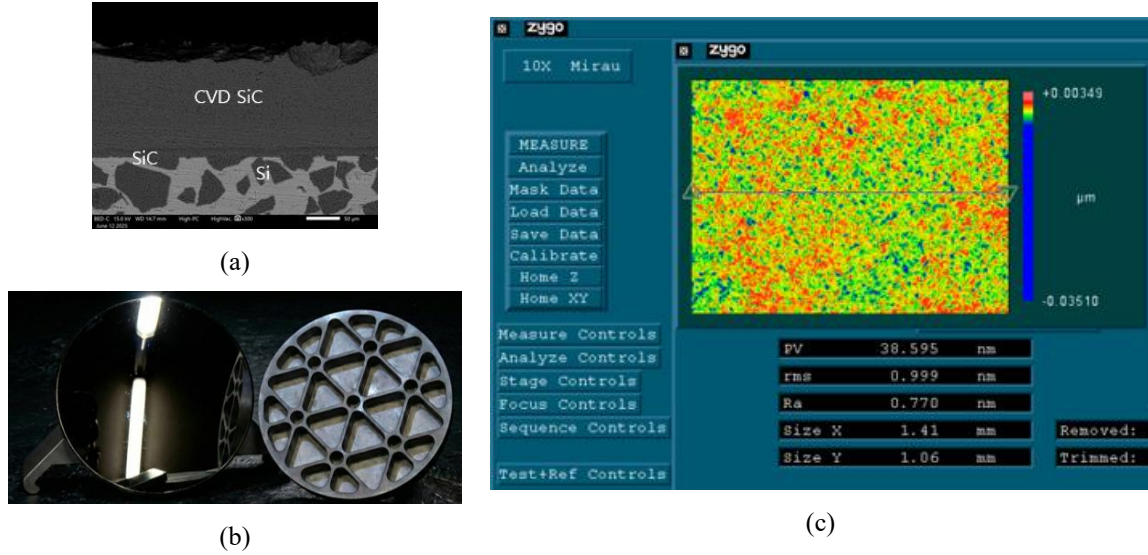


Figure 5. CVD SiC coating and local optical surface preparation results. (a) Cross-sectional image of a CVD-SiC-coated SiC-based substrate. (b) Polished Si-SiC mirror and representative mirror-back geometry after downstream processing. (c) Local surface metrology result of a CVD-SiC-coated and polished SiC sample measured using a Zygo white-light interferometric microscope.

5. DISCUSSION

The main significance of this work is the integration of binder jet printing, densification, machining, CVD SiC coating, and polishing into a continuous process chain for SiC optical components. In this route, binder jetting defines the ceramic preform geometry, densification provides mechanical integrity, machining refines the reference geometry, and CVD SiC coating provides a high-purity surface layer for optical finishing. This separation of roles is important because the printed or densified SiC surface is not assumed to be directly suitable for optical use. Si-SiC and porous SiC substrates can contain residual phases, pores, local density variations, and machining marks; therefore, CVD SiC coating is used as a functional bridge between the AM substrate and the final polished surface.

SiC offers high specific stiffness, thermal stability, and environmental resistance, which are attractive for compact spaceborne optical systems where aperture, mass, and dimensional stability must be balanced. Compared with aluminum AM mirrors, SiC is more difficult to print, densify, machine, and polish, but it provides higher stiffness and improved thermo-mechanical stability. Compared with conventional SiC mirror fabrication, binder jetting can provide greater geometric freedom at the preform stage, especially for integrated mirror backs, housings, baffles, and support features. Before application to mission-specific optical hardware, powder spreading, green-part uniformity, residual phases, porosity, coating uniformity, polishing allowance, full-aperture figure, WFE, and environmental performance must be evaluated.

6. CONCLUSIONS

This paper presented a process-development route for additively manufactured SiC optical mirrors and structural components. A dedicated binder jetting platform was used to process non-spherical and abrasive SiC powders, and the printing process was integrated with curing, depowdering, densification, machining, CVD SiC coating, and optical surface preparation. LSI provides a route to Si-SiC components with limited dimensional change, while CVI provides a route toward silicon-free porous SiC components where material purity and dimensional stability are important. CVD

SiC coating was treated as a functional bridge between heterogeneous or porous SiC-based substrates and the final optical surface, with a typical coating thickness of 150–300 μm targeted to provide polishing allowance.

Representative samples demonstrated the feasibility of progressing from binder-jetted SiC preforms to surface-prepared SiC-based components. The as-printed structural part and all-SiC assembly concept illustrate the intended direction toward integrated optical and structural components, while the polished Si-SiC mirror and local metrology result demonstrate reflective surface preparation. A selected CVD-SiC-coated and polished area showed local RMS surface roughness of 0.999 nm and Ra of 0.770 nm. The present work should be interpreted as an early-stage manufacturing and surface-preparation demonstration rather than full optical qualification; future work will focus on full-aperture figure measurement, wavefront error evaluation, coating uniformity, dimensional repeatability, thermal-vacuum testing, vibration testing, and mission-specific structural design.

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