

# FABRICATION OF FREEFORM SILICON CARBIDE COMPONENTS BY HYBRID MANUFACTURING

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## ABSTRACT

In this paper, it is shown that hybrid manufacturing can produce a freeform surface on silicon carbide (SiC) preforms printed using binder jet additive manufacturing (BJAM). While additive manufacturing methods, such as BJAM, can fabricate complex geometries, machining or grinding is still required to achieve the desired surface finish and geometry. Hybrid manufacturing has been proven to be an efficient method to address these issues. However, hybrid manufacturing faces its own issues dependent on the combination of processes. When the subtractive and additive manufacturing steps are completed in two separate systems, for example, a common coordinate system must be defined for part transfer. This is challenging, because AM preforms do not inherently contain features that can be used for accurate part location. Additionally, it must be confirmed that the intended final geometry is contained within the AM preform. This paper addresses issues for AM + machining.

## KEYWORDS

Additive manufacturing, binder jet, milling, silicon carbide, hybrid manufacturing, structured light scanning, machining dynamics

## INTRODUCTION

A silicon carbide (SiC) preform with a toroidal freeform surface was fabricated using binder jet additive manufacturing (BJAM) and then infiltrated with cyanoacrylate. This enabled handling and machining of the preform [1]. A novel method for coordinate system definition using structured light scanning is detailed [2]. The SiC preform was scanned while clamped in a vise and specific features on the vise were selected to define the local coordinate system. This coordinate system was then located in the milling

machine using an on-machine probe. This method overcomes typical issues with hybrid manufacturing, enabling accurate alignment of the digital design (i.e., CAD model) with the AM preform scan model. The structured light scan and coordinate system also enable toolpath generation and simulation.

Surface finish is of primary interest for optics applications. Freeform optics have been proven to be a disruptive technology in the optics industry to reduce components, system size, improve performance, and enable new functionality [3]. Additionally, AM SiC has been demonstrated to be applicable to optics applications [3]. Therefore, average roughness was measured before and after rough machining using an optical 3D microscope. A time domain milling simulation is compared to experiment. This work demonstrates and evaluates the proposed method of coordinate system definition and transfer for hybrid manufacturing of BJAM SiC freeform surfaces.

## PRE-MACHINING

The following subsections detail efforts prior to machining of the SiC preform. Definition and fabrication of the preform, an initial structured light scan, and computer aided manufacturing (CAM) steps are detailed.

### Freeform definition

The surface was modeled using the toroidal freeform described in Equation 1:

$$Z = \frac{C_x X^2 + C_y Y^2}{1 + \sqrt{1 - C_x^2 X^2 - C_y^2 Y^2}}, \quad (1)$$

where  $C_x$  and  $C_y$  are constants. The modeled surface is shown in Fig. 1. To enable printing, a

12.7 mm tall base from the surface's lowest point was added; see Fig. 2.

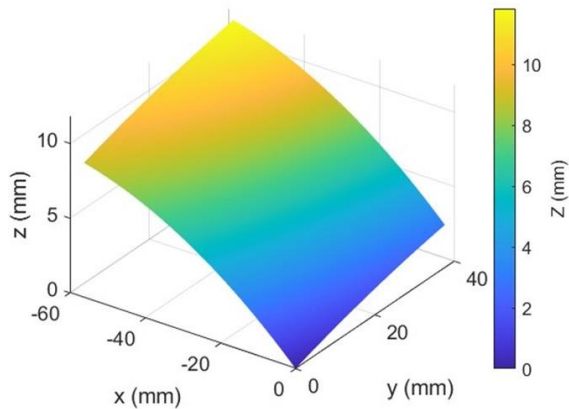


FIGURE 1. Surface modeled for printing and study from Equation 1.

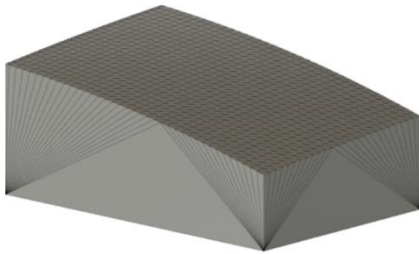


FIGURE 2. Final CAD model with 12.7 mm tall base.



FIGURE 3. Silicon carbide sample as printed from BJAM (left) and after infiltration (right).

### **BJAM sample preparation**

The sample was printed using an ExOne X25Pro BJAM system; see left panel of Fig. 3. Since the sample had open porosity and was fragile, it was infiltrated with approximately 75 mL of cyanoacrylate prior to machining. The sample after infiltration is shown in the right panel of Fig. 3. After 24 hours of drying, exhausted cyanoacrylate was lightly brushed off. The

sample was then clamped in a 101.6 mm wide milling machine vise as shown in Fig. 4.



FIGURE 4. Infiltrated sample clamped in milling machine vise.

### **Structured Light Scanning**

A structured light scan of the preform clamped in the vise was then taken for work coordinate system (WCS) definition and stock model generation. A GOM ATOS Core 200 was used to perform this scan after placing 1.5 mm scanner targets around the vise and spraying with AESUB blue vanishing scanning spray. The preform was covered to ensure it was not coated. GOM Inspect was then used to align the CAD model described by Eq. 1 to the scan using a best fit alignment. The WCS was found by fitting planes to three ground surfaces on the vise. The WCS, CAD to scan alignment, and scan are shown in Fig. 5.

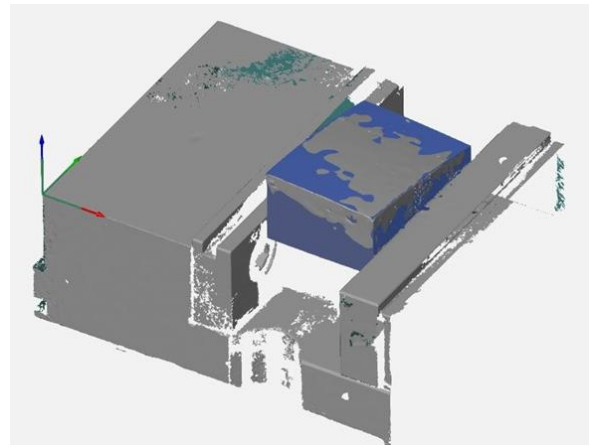


FIGURE 5. Scan of preform in vise with CAD aligned and WCS defined.

### **Milling parameter selection**

A 2.381 mm diameter, two-flute ball end mill (YG1 model 99573) was selected to machine the preform. This tool had a diamond coating for milling SiC. The CAD model was shifted down 0.5

mm relative to the scan to set the depth of cut. Feeds and speeds were selected based on the manufacturer's specifications and the max speed of the Haas OM2 three-axis CNC machining center used for this study. This resulted in a selection of 30,000 rpm (225 m/min surface speed) and 0.015 mm/tooth feed per tooth (881 mm/min feed rate). A 0.193 mm stepover was selected to provide a theoretical average roughness of  $1\ \mu\text{m}$  for the machined part based on a simulation of the milling process. This resulted in 15 minutes of cut time.

To ensure these parameters would result in a stable cut, the tool was tap tested to measure its frequency response functions in both the X and Y directions. The limiting cutting depth for the chosen parameters was over 70 mm, therefore, machining stability was not a concern for this setup [4].

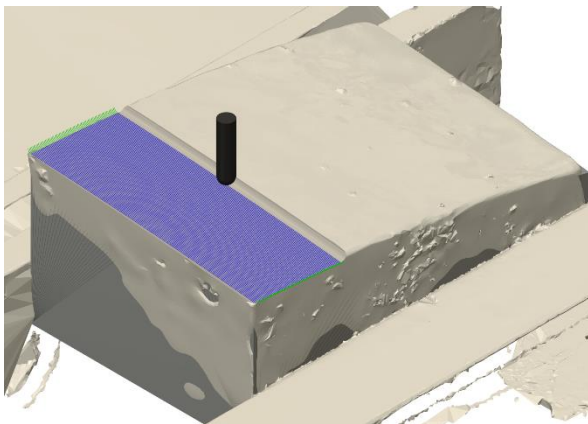


FIGURE 6. CAM simulation using the scan as the stock model.

### **CAM**

The CAD and scan model files using the WCS defined by the vise surfaces were exported from GOM Inspect and imported into Fusion 360 for CAM programming. The WCS was set as the model origin and model orientation. A parallel finishing type operation was selected that keeps passes parallel in the XY plane and follows the surface in the Z direction. The scan enabled a full simulation of the programmed tool paths; see Fig. 6.

A Haas OM2 three-axis CNC machining center retrofit with industrial ventilation was used to machine the preform. The vise with preform was clamped to the machine table and aligned to the machine X and Y axes using a dial indicator. The

WCS was identified using a Haimer 3D sensor that was previously calibrated to be zero at the centerline of the spindle. The X and Y faces were zeroed in the machine when the 3D sensor read zero on their respective faces. The Z was zeroed by finding the distance between the programmed Z surface and the machine table; see Fig. 7.

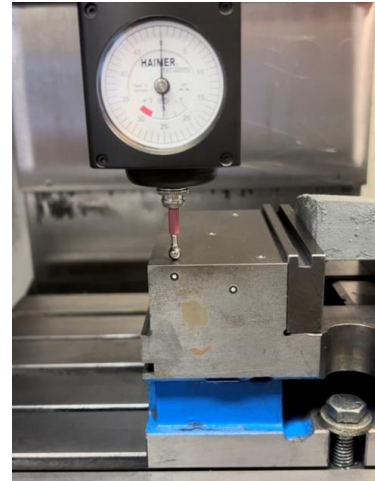


FIGURE 7. Probing of top surface to find WCS Z zero using 3D sensor.

### **POST-MACHINING**

The following sections describe post-machining activities. A final 3D scan with surface comparison to CAD model, a point-to-point comparison to the equation, and surface roughness results are detailed.

#### **Surface comparison**

The machined SiC sample was again scanned with a GOM ATOS Core 200 while clamped in the vise. This enabled the vise coordinate system to be defined in the same method previously described. The CAD model was oriented in the same position and orientation relative to the WCS as it was before machining. This provided a comparison of commanded and machined surfaces; see Fig. 8. The result shows that the surface was over cut by approximately  $20\ \mu\text{m}$  to  $60\ \mu\text{m}$ .

#### **Point-to-point comparison**

A grid of 88 surface points was created on the surface to enable a direct comparison to Eq. 1. The grid points space at 5 mm intervals and centered on the surface. The X and Y values for these points were input to the original equation to calculate a theoretical Z value. The actual Z value from GOM Inspect was subtracted from the

theoretical Z value. A 3D plot of this result is shown in Fig. 9. The mean error was 45  $\mu\text{m}$ .

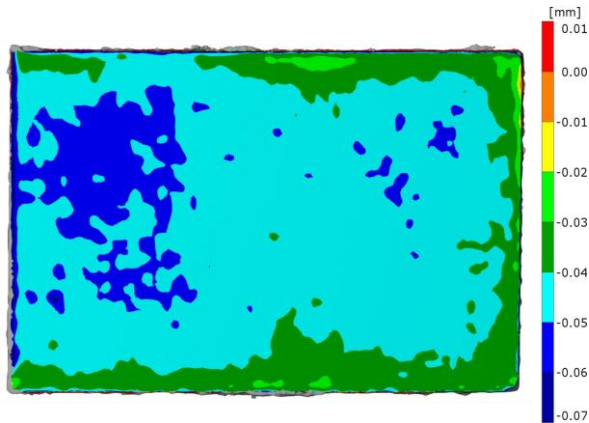


FIGURE 8. Surface comparison of expected vs. as machined.

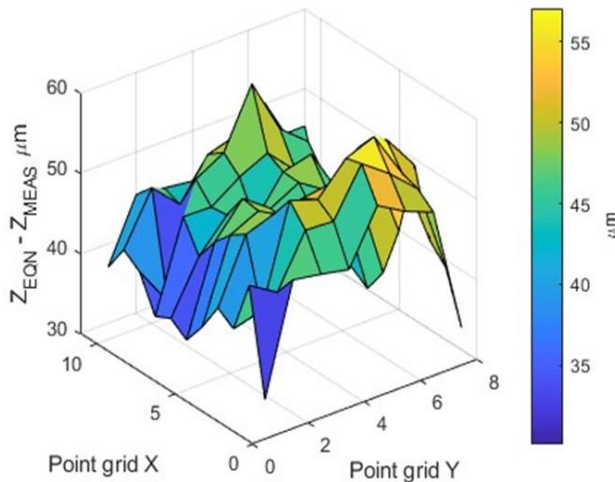


FIGURE 9. Theoretical Z value minus actual Z value for grid of points.

Table 1. Results for surface roughness before and after machining.

Ra before machining ( $\mu\text{m}$ )	Ra after machining ( $\mu\text{m}$ )
34.6	9.7
31.1	9.5
30.1	9.3
38.9	8.9
38.1	7.7

### Surface roughness

An Alicona InfiniteFocusSL 3D measurement system was used to compare the surface finish before and after machining. Five traces were taken that conformed to ISO 4287 and 4288. A cutoff wavelength of 8000  $\mu\text{m}$  was used pre-machining and 2500  $\mu\text{m}$  was used post-machining. These results are provided in Table 1. It should be noted that the BJAM SiC particles ranged from 30  $\mu\text{m}$  to 40  $\mu\text{m}$  in diameter. Recall that a 0.193 mm stepover was selected to give a theoretical average roughness of 1  $\mu\text{m}$  based on the milling process.

### DISCUSSION

This work demonstrates hybrid manufacturing of a freeform SiC BJAM sample using structured light scanning and a vise as a fiducial for machining coordinate system definition and transfer. The structured light scan and fiducial provide an accurate stock model for machining simulation and alignment of CAD within the preform.

Measurements of geometry and surface finish post-machining show residual errors. The surface comparison generated from scanning the surface post-machining showed error from original CAD alignment on the order of 20  $\mu\text{m}$  to 60  $\mu\text{m}$ . Average roughness of the sample post-machining from the 3D microscope traces were approximately 10  $\mu\text{m}$  compared to a theoretical average roughness of 1  $\mu\text{m}$  based on milling parameters selected. We propose several explanations for these errors, including thermal deformation of the milling machine during the milling process, tool wear, age and wear of the milling machine itself, error in reacquisition of the coordinate system when placed in the milling machine, and size of the SiC particles.

The final steps of grinding and polishing are not addressed here, but can be included in following research using the proposed methodology for BJAM of SiC freeforms.

### CONCLUSIONS

In this paper, a BJAM SiC toroidal freeform surface was produced using hybrid manufacturing using structured light scanning and milling. The vise included in the structured light scan served as a fiducial for WCS definition and acquisition within the milling machine. The toroidal surface was defined using an equation to enable direct comparison to machining results. Milling parameters were verified to be stable by

using tap testing and machining dynamics calculations. Error in geometry and surface finish are presented. A point grid was generated to directly compare Z height results post-machining to the original equation and alignment. Overall, the methodology is proven to be successful for rough machining of BJAM SiC samples before grinding and/or polishing.

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