INTERNAL FEATURE DESIGN FOR INCREASED DAMPING BY CAPTURED POWDER

Gregory Corson[1], Brett Compton[1], Michael Gomez[2], and Tony Schmitz[1,2]
[1]Mechanical, Aerospace, and Biomedical Engineering
University of Tennessee, Knoxville
Knoxville, TN 37996, USA
[2]Manufacturing Science Division
Oak Ridge National Laboratory
Oak Ridge, TN 37830, USA

INTRODUCTION

This paper describes the design of internal features for powder bed fusion (PBF) printed structures with captured feedstock powder. The designs are tailored to increase damping and, therefore, dynamic stiffness for additively manufactured components. Additive manufacturing (AM) has gained global attention and is being implemented across multiple industries and disciplines. It enables complex internal and external geometries, a reduced number of components, and material minimization in comparison to parts produced by sole machining from wrought blanks. In the PBF process, an energy source is used to scan and fuse planar cross-sections of the design geometry as consecutive feedstock powder layers are exposed. Prior research has shown that intentional retention of powder within a PBF structure can provide significant energy dissipation, or damping, as compared to solid, monolithic counterparts [1–3]. Increased damping serves to improve dynamic stiffness which increases fatigue life and machinability of AM components. Other research has shown that the mode shapes of structures with captured powder can be modified through the inclusion of internal supports [4].

This research studied the effect of free-standing internal features and the potential for increased damping through their interaction with retained feedstock powder using PBF. Four designs were studied with the same nominal external geometries, 100 mm long rectangular posts with 30 mm by 20 mm cross-sections. The internal geometries included: solid and powder cores with {no ribs, ribs normal to long edge (for shear damping), ribs normal to short edge (for compression damping)}. The modal damping ratios for dominant vibration modes for each design were extracted from free-free boundary condition modal impact testing. The inclusion of feedstock powder and internal features produced damping ratio increases by factors of 26 to 28 over the solid geometry.

DESIGN

Features were incorporated inside structures with the same external dimensions and nominal core of captured powder. Unlike previous research, the designs focused on free-standing, solidified internal features (i.e., free to move relative to the external structure). These designs were intended to add damping through captured powder interaction without significant detriment to the static stiffness. Computer aided design (CAD) and finite element analysis (FEA) were performed using SOLIDWORKS™. The FEA simulations were used to guide the design process by observing the free-free vibrational behavior of the solidified post. Figure 1 shows the identical external dimensions for design. Figure 2 shows the first free-free bending mode shape for the solid post with a natural frequency of 6392 Hz. The mode shape agreed with FEA predictions and provided the motivation for the internal structure designs. Similar agreement with FEA predictions was observed for modes from these designs.

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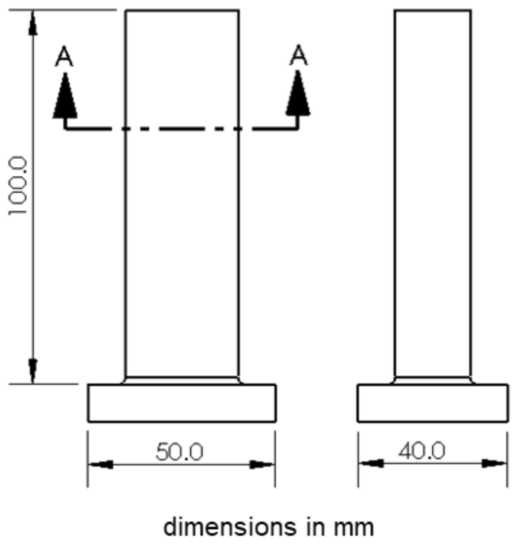

FIGURE 1. External geometry of PBF posts and section A-A location in Figure 4.

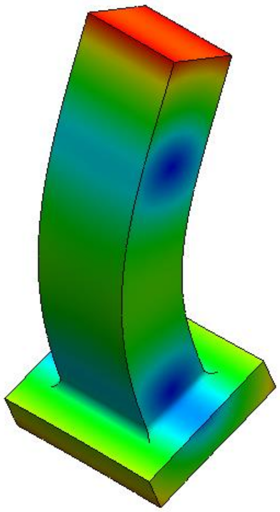

FIGURE 2. First free-free bending mode shape for solid post with 6392 Hz natural frequency.

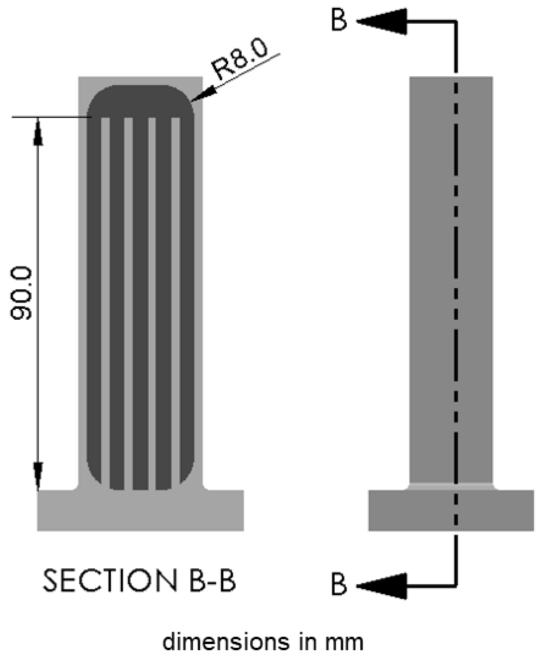

FIGURE 3. Internal view of shear rib design. Vibration test direction was into the page.

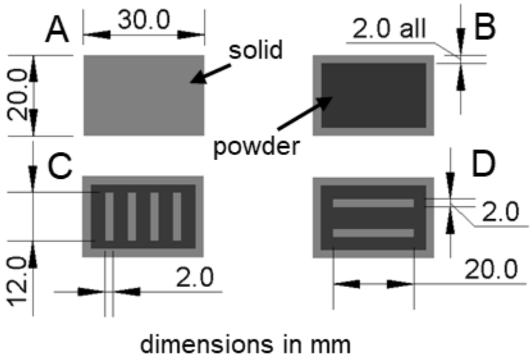

FIGURE 4. Post section A-A from Figure 1: A) solid; B) powder only; C) shear (shear damping); and D) normal (compression damping).

Figures 3 and 4 display the internal geometries of the different designs. The first two designs (A and B in Figure 4) are simple: solid and captured powder. The second two designs include internal, free standing ribs that are not attached to the surrounding walls. As the name suggests, the "shear" ribs were intended to shear the flow of powder as the external structure was excited at its first free-free bending mode shape; see Figure 2. This obstruction in the powder flow of the powder was expected to add damping. The "normal" ribs were oriented normal to the excitation direction and therefore provided powder compression during motion in the first free-free bending mode shape. The intent of this design was to “squeeze” the powder and support or recruit additional powder that was not excited in the no-rib, captured powder design. As shown in Figure 3, the normal and shear clamped-free ribs protruded from the base with a height of 90 mm and were surrounded by the captured powder. Additionally, 8 mm internal fillets were included to assist the printing process; see Figure 3.

EXPERIMENTAL SETUP

The structures were fabricated by laser PBF using a Concept Laser M2 Cusing with stainless steel 316L powder produced by Praxair Surface Technologies. The powder size distribution was {15-45} µm with a spherical morphology and was produced by gas atomization.

The frequency response function (FRF) was measured for each printed structure using impact, or tap, testing, where a modal hammer (PCB model 086C04) was used to excite the structure and a low-mass accelerometer (PCB model 352C23) was used to measure the vibration response. The direct FRF, where the hammer and accelerometer are spatially co-located, was measured at the central, top edge of each beam as shown in Figure 5. The structures were placed on soft foam pads to approximate free-free boundary conditions.

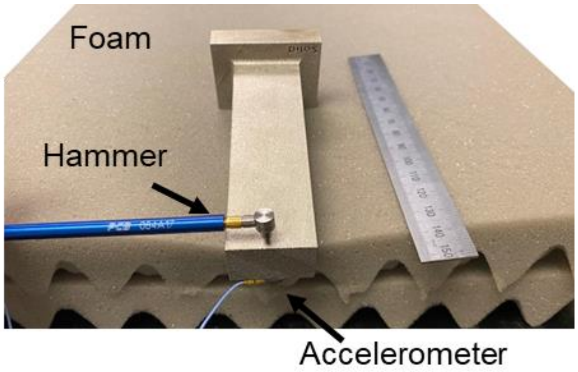

FIGURE 5. Free-free boundary condition tap testing setup for PBF posts.

RESULTS AND DISCUSSION

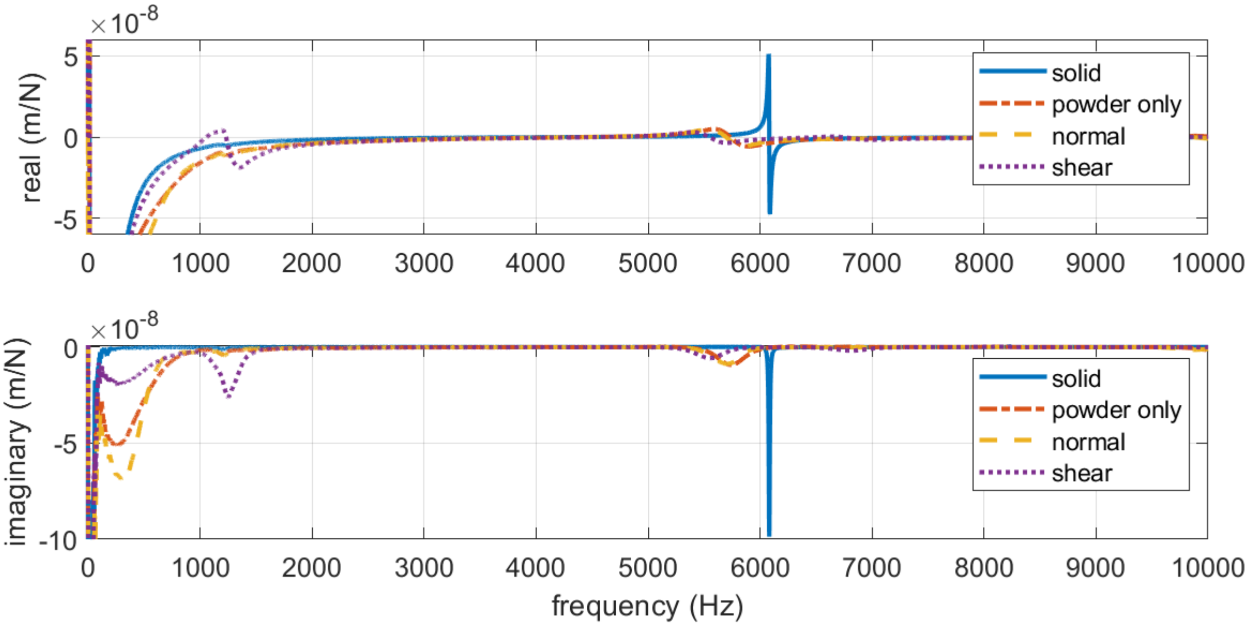

FIGURE 6. Direct FRFs for PBF posts.

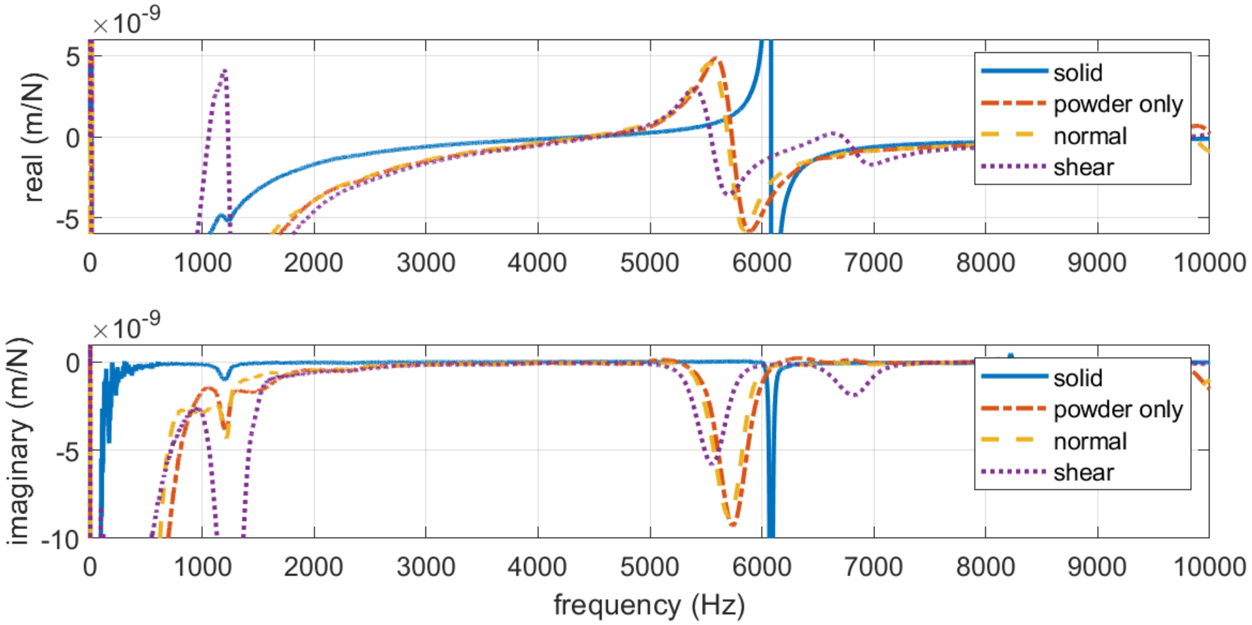

FIGURE 7. Zoomed view of Figure 6 to highlight the direct FRF measurements of PBF posts containing captured powder.

TABLE 1. Best-fit modal parameters for the PBF posts.

Design	Mode	f_n (Hz)	k_q (N/m)	m_q (kg)	ζ_q
solid	1	6082	5.03×10^9	3.45	0.001
powder only	1	5741	2.06×10^9	1.58	0.026
normal	1	5708	2.10×10^9	1.63	0.027
shear	1	5555	3.15×10^9	2.58	0.028
	2	6820	1.23×10^{10}	6.71	0.022

Figure 6 shows the direct FRF measurements for each of the PBF posts (free-free boundary conditions). The solid post's first natural frequency is observed at 6082 Hz, similar to the FEA prediction of 6392 Hz. This demonstrates that the foam foundation provides a reasonable free-free boundary conditions approximation. As expected, the solid post was lowly damped; this is shown by the sharp peaks in both the real and imaginary parts of the complex-valued FRF. The larger peak heights for the solid post's response also show that this structure provides much lower dynamic stiffness than the geometries with captured powder.

Figure 7 shows the FRFs for the posts with captured powder in more detail. The peak heights for the posts with captured powder are significantly smaller than the solid post. The natural frequencies are also lower. The captured powder post response peaks in Figure 7 are also significantly wider, indicating the captured powder provides considerable damping and increased dynamic stiffness.

The modal parameters for each FRF were obtained by a peak picking fitting procedure [5]; the results are listed in Table 1, where f_n is natural frequency, k_q is modal stiffness, m_q is modal mass, and ζ_q is the modal damping ratio. The modal damping ratio for the solid post is 0.001, or 0.1%. This is anticipated for metallic, monolithic components.

Table 1 shows that the captured powder provided an increase in damping by factors of 26 to 28 as compared to the solid post. The shear rib configuration provided increased modal stiffness and damping as compared to the normal ribs and powder-only posts. There is also a second mode for the shear rib design at 6820 Hz. An FEA investigation into the dynamic nature of the clamped-free internal geometry predicted a natural frequency near 6700 Hz in the excitation direction of the external structure. Figure 8 displays the corresponding clamped-free mode shape for the shear ribs. This mode resembles the traditional second mode shape for a clamped-free (cantilever) uniform cross-section beam.

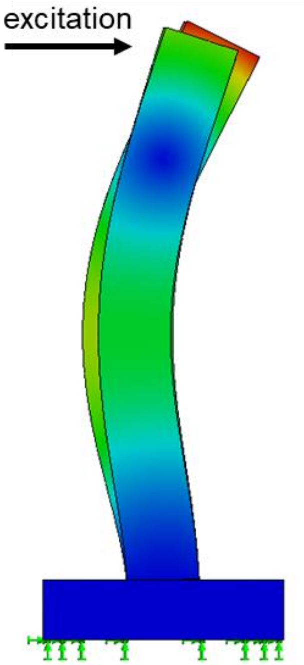

FIGURE 8. Clamped-free mode shape for shear ribs.

The 6820 Hz mode for the shear rib (mode 2 in Table 1) demonstrates that the dynamics of internal features contribute to the dynamics of the entire structure. This provides insight into future design possibilities.

CONCLUSIONS

This paper investigated the use of intentional captured powder during powder bed fusion printing of prismatic structures to increase damping and, therefore, dynamic stiffness. Finite element analysis was used to predict the natural frequencies and mode shapes for free-free boundary conditions. Internal features were proposed to provide additional energy dissipation through increased powder interaction. The post designs were printed and free-free tap testing was used to identify modal parameters, which were compared for each design. It was shown that captured powder and internal features provided significant damping and increased dynamic stiffness. It was also shown that the dynamics of internal free-standing features could be used to tailor the dynamic response of the overall structure.

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