

Accurate Alignment of Metal Binder Jetted Part Assemblies

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Abstract

Metal binder jet 3D printing can produce complex geometries with high resolution. However, design limitations in binder jetted structures can make it necessary to split assemblies into multiple parts that will later be joined through sintering or infiltration. This creates a need for precise alignment when joining small parts or parts with fine features as misalignment can compromise the functionality of the final structure. This study evaluates the alignment accuracy of two stacked plates, the top part measuring 30 mm by 40 mm, supported by four printed alignment features. The alignment features are 1.7 mm diameter cylindrical posts that fit into erodible star-shaped holes. Four samples were printed to assess alignment accuracy and repeatability, providing a basis for evaluating the feasibility of binder jet printing for mechanically joined or assembled small parts. Results showed that alignment was on average 0.03 mm and did not go over 0.1 mm of the target position for all measured dimensions.

Introduction

Binder jetting is an additive manufacturing technique that creates parts by spreading fine powder layer by layer and uses inkjet printing to apply a binder to specific areas, forming the desired shape [1]. The “green” or printed part is fragile and requires some processing to achieve the desired part quality [2]. This can include curing the part in the powder bed, and sintering after the part is cleaned [3, 4]. Some advantages of binder jetting over other additive manufacturing techniques are that a wide range of materials can be used, the process doesn’t use high energy sources, and parts can be made quickly. The binder used can also be changed to achieve different part properties, and tuned across a part [5, 6, 7]. Parts can also be strengthened by infiltration, resulting in a composite final material [8, 9].

However, a fundamental limitation of this process arises when attempting to fabricate enclosed internal voids. The method of layer-by-layer powder deposition across the entire build area precludes the direct creation of hollow features within a single printed part. For instance, it is impossible to directly print a hollow sphere without trapping loose powder. Consequently, designs necessitating internal spaces or channels, crucial for applications such as microfluidic systems, typically require a multi-part design approach [10]. These individual components, each containing a portion of the desired internal geometry, must then be assembled. While avoiding the problem of internal voids, this assembly process introduces significant challenges, particularly concerning the precise alignment of the mating surfaces at the interfaces between the assembled parts. In the realm of microfluidics, where intricate networks of micro-scale channels

dictate device functionality, achieving accurate alignment during the assembly of multiple printed components is extremely important. Even minor misalignments can disrupt fluid flow or even lead to leaks, compromising device performance.

This research investigates a novel design methodology to achieve precise alignment for multi-plate microfluidic systems fabricated using metal binder jetting. Traditional pin-and-hole alignment methods often result in breakage due to the fragile nature of green-state parts. We propose integrating self-centering, eroding, star-shaped features into the design of mating components. This strategy enables a low-force, gravity-assisted assembly, significantly reducing the risk of part damage while ensuring precise alignment. As a mating cylindrical post is inserted, the star-shaped hole erodes slightly, progressively centering the parts. We quantify the achievable alignment accuracy of this method, demonstrating its suitability for applications like microfluidics where strict dimensional tolerances are required to maintain channel integrity. Our findings provide a practical solution to a known geometric limitation of the binder jetting process, demonstrating the feasibility of this approach for successful assembly of binder jet-printed components.

Design

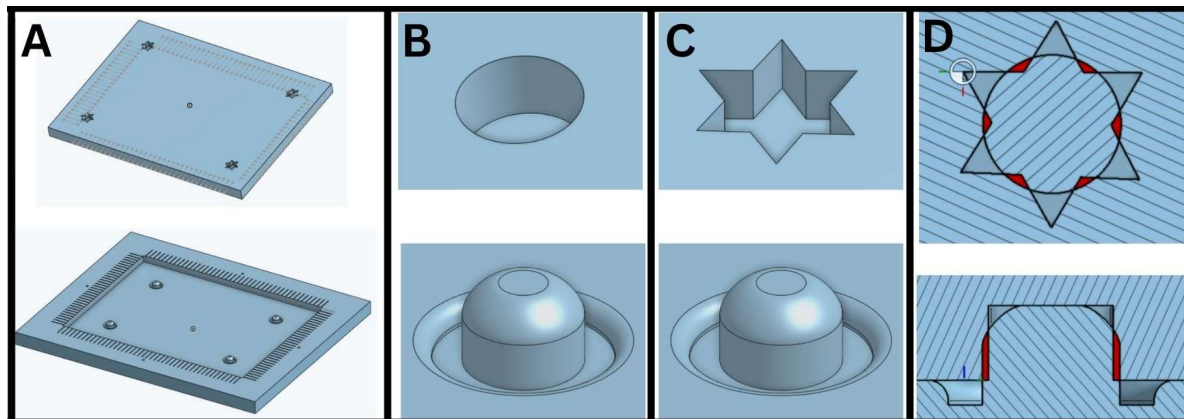


Figure 1: A) Isometric view of the top of the bottom plate (top) and the bottom of the top plate (bottom). B) Circle hole (top) and rounded post with moat (bottom). C) Star-shaped holes (top) and rounded post with moat (bottom). D) Cross section of post inserted in star hole, the areas in red show the contact points designed to erode where the parts overlap. Horizontal cross section (top), vertical cross section (bottom)

A part assembly was designed and fabricated to evaluate the precision of this alignment method. The assembly consists of 2 plates, the bottom plate measuring 50 mm by 60 mm and the top plate measuring 30 mm by 40 mm. The sizes of these plates were chosen mainly for ease of handling and ability to be visually inspected.

The alignment features consisted of 4 identical cylindrical posts, 1.668 mm in diameter and 1.20 mm tall measuring from the bottom of the 0.3 mm deep circular depression on the bottom plate. The height was chosen to be less than the thickness of the plate, while still ensuring that there is sufficient structural support. As seen in Figure 1, the posts have a rounded edge at the top to aid in aligned assembly and a circular depression to catch powder that falls off or is eroded off the mating hole during assembly without interfering with the part alignment.

The first version of the assembly was designed with cylindrical posts in the bottom plate that fit into equal diameter cylindrical holes in the top plate (illustrated in figure 1B). Because the posts and the holes were of equal size, pressure had to be applied in order for the plates to sit flush against each other. A problem that arose with this design was fragility. Because assembly was done with green parts, having posts that fit snugly into holes frequently led to one or both of the plates breaking. Making the post smaller or the hole bigger would introduce alignment errors. To address the insertion force problem, a star shaped hole design was developed.

The 6-pointed star-shaped holes (illustrated in figure 1C), facilitate aligned insertion of the posts with minimal force. The diameter of the inscribed circle in the star is 1.44 mm and the diameter of the circumscribed circle around the star is 2.50 mm. As the posts are inserted, the contact points of the star slightly erode (figure 1 D shows in red the contact points that interfere and erode). The sharp, thin points of the star were designed to offer minimal resistance during insertion. This eroding action progressively increases the contact area between the cylindrical post and the remaining structure of the hole, guiding the post to be centered on the star. This increasing resistance, combined with the multi-pointed geometry of the star arms, facilitates a self-centering effect, aiming for accurate lateral alignment of the two plates. This over-constrained design for assembly in the fragile "green" state of binder-jetted parts uses six contact points on four star-shaped holes for a total of 24 contact points with the intention of averaging over variations in printing. The circular depression surrounding the posts on the bottom plate serves as a collection area for the eroded powder, allowing the two plates to sit flush, stable contact.

Methods

Parts were printed on an ExOne Innovent+ printer using SS316L powder and ExOne Aquafuse binder. During printing, a 75% binder saturation and 40 μm layer thickness were used. After the parts were printed, they were cured for 1 hour and 40 minutes at 180°C. Powder was removed by carefully brushing the parts with a paintbrush, then gently blowing compressed air into the smaller features of the design through a small blunt-tipped syringe needle. Then the parts were manually assembled by carefully placing the top plate onto the bottom plate and allowing gravity to bring the parts into contact. Manual pressing was avoided to limit potential application of lateral forces.

Once the parts were assembled, they were imaged using a Keyence VHX-7000 microscope on 20 times magnification to determine alignment accuracy. For measurement purposes, the sides of the rectangular parts were labelled based on the orientation while imaging with the microscope. The far side during imaging was designated as the top side, and the close side was designated as the bottom side. The top and bottom are the long sides of the rectangle. Right and left were designated as the right and left sides of the part during imaging; they are also the shorter sides of the rectangle. The measurements were made using the distance between the marked middle of the two parts in relation to each other, and the separation distance between the two plates. These two numbers give a coordinate for the middle of each side of the parts that can be used to assess the accuracy of this alignment method. Given the rectangular shape of both

plates, the top and bottom measurements indicate how far to the left or right the middle of the top plate is while the measurement on the right and left sides indicates the vertical misalignment of the plates. These measurements are also indicators of how well two printed parts match up with each other. This is important in aligning multiple printed parts because the printed dimensions do not exactly match the CAD design.

Results

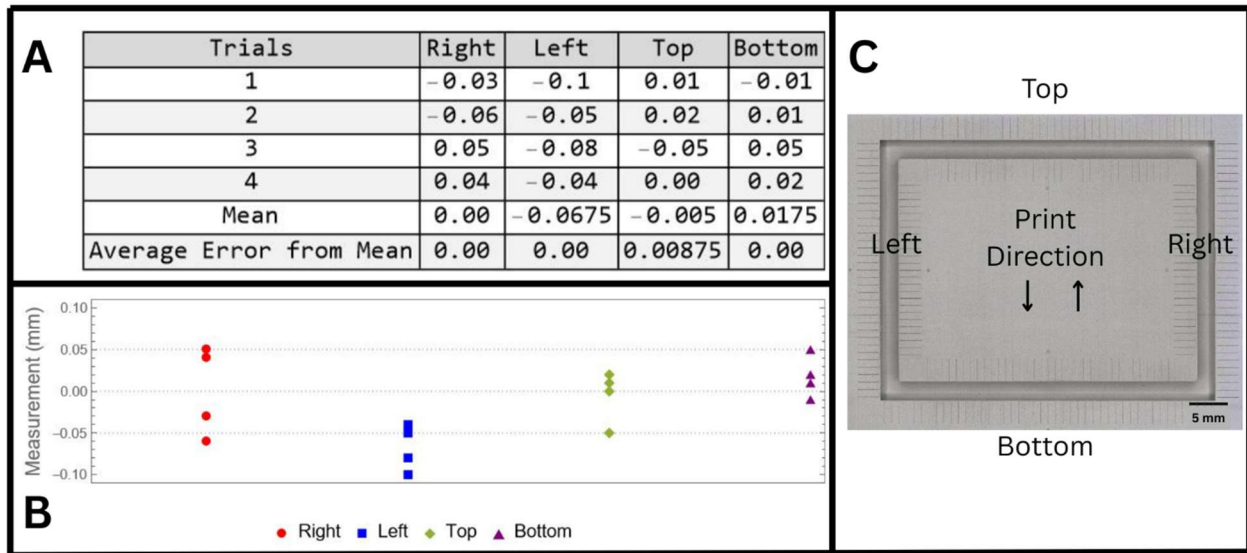


Figure 2: A) Table of measured alignment. B) Graph of measured alignment. C) Figure showing label directions on an assembled part.

The post in the star-shaped hole alignment design gives, on average, misalignment of 0.03 mm. The table in figure 2 displays the measured alignment of each side of the parts made. Positive is measured in the upward and rightward directions. The largest misalignment observed was the left side of trial 1, which was 0.1 mm off. There does not seem to be much of a difference between the alignment of the top and bottom and the right and left. But left is the side with the mean furthest from the desired position, which could be due to the fact that the printhead moved from top to bottom while printing. Moving like this, the printhead leaves a line of binder going from the top to the bottom, which in this case, would make the measurements of right and left movement more consistent [11].

Figure 3 (A and B) shows the star hole both before and after having a post inserted and removed. In figure 3 B where the post has been removed from the top plate, the star-shaped holes show erosion as expected. Even though the star shape is still clearly visible, the inner tips of the star are no longer there on any side, and the hole almost appears hexagonal. The sides of the hole also appear to be slightly sloped, which is what we would expect to see from a post with a curved top. It is worth noting that because the post is made out of the same materials as the star, it also erodes as it moves deeper into the hole, which also matches with what we see in figure 3 C below.

Because of the fragility of the green parts, sometimes when the top was removed after measurement, the post from the bottom plate broke off, remaining in the star-shaped hole. Figure 3 D shows this situation, allowing us to see how the post and star hole fit together. Firstly, the post appears to be well centered on the star-shaped hole. Secondly, the jagged edges seen on the bottom left corner indicate that the star eroded as the post was inserted.

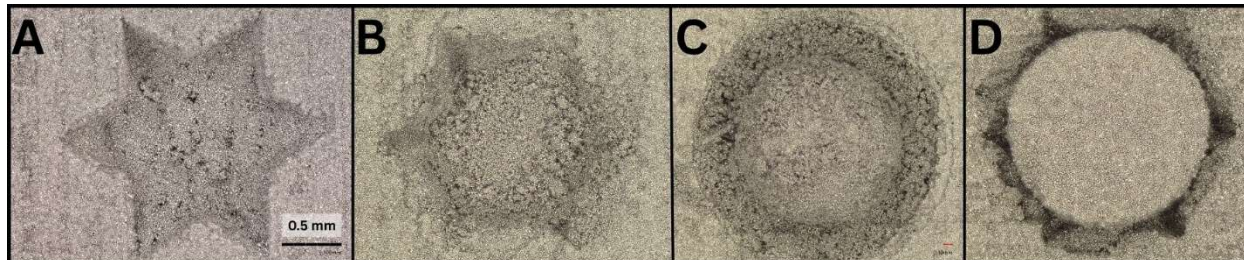


Figure 3: Printed alignment features. From the left they are 1) a star hole after printing 2) a star hole after having a post inserted and removed 3) a post after being inserted and removed 4) a post stuck in the star hole.

Figure 3 C shows an optical image of the post after insertion and removal. We can see that the circular depression now contains eroded powder but may not have a large enough outer diameter as the eroded powder fell beyond the outer edge. We also see some indication of erosion on the surface of the post but much less than the erosion of the star contact points. Overall, the images offer support that the contact tips of the stars erode, and center the cylindrical posts under gravity-based assembly of these small parts. This suggests that the alignment approach is not only precise, but also robust and these findings point to the broader applicability of eroding mechanical alignment features in other precision-assembled binder jet components, especially those involving channels or interfaces that cannot tolerate misalignment.

Conclusion

This study demonstrates a novel and effective alignment method for assembling metal binder-jetted green parts. By employing an over-constrained alignment scheme consisting of cylindrical posts inserted into eroding star-shaped holes, we achieved a high degree of precision with minimal insertion force. On average the alignment accuracy was measured to be 0.03 mm, with a maximum error of 0.1 mm. This level of precision is critical for the formation of millimeter-scale microfluidic channels at the interface between parts. The printed alignment features worked as intended, with the star tips eroding and the posts self-centering under the force of gravity alone. This approach enables the direct integration of alignment features into binder-jetted parts without the need for additional post-processing or hardware. The findings not only validate the proposed design but also point to the broader applicability of eroding mechanical alignment features in other precision-assembled binder jet components.

While this study successfully demonstrates the feasibility of our alignment method in the fragile green state, it is important to acknowledge certain limitations and outline future work. The current investigation was restricted to a single alignment feature geometry, and future research should explore a wider variety of designs to optimize the self-centering and eroding properties. One next step should be to quantify the alignment accuracy after sintering. An aligned green part is necessary for a successful final assembly, but dimensional changes during the high-

temperature sintering process could affect alignment and must be measured and accounted for. Further studies should explore the effects of process variability, such as print parameters and powder consistency, on the alignment accuracy. They should also look into taking out the manual placement of the plates to remove human error. This will provide a more comprehensive understanding of the method's robustness and help establish a reliable and repeatable assembly process for complex, multi-part binder-jetted systems.

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