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Formation of Easy-To-Remove Supports in Laser Powder Bed Fusion through Selective Doping

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Abstract

Laser Powder Bed Fusion (LPBF) is a popular Additive Manufacturing (AM) technique used commonly for metals. Metal parts formed by LPBF generally require supports connecting the part to the print bed to hold up the structure, remove heat, and minimize deformation due to solidification shrinkage. Because of these supports, finished parts must be cut away from the build plate, and generally require additional machining to achieve the desired geometry. In this study, a carbon suspension was deposited in the 316L stainless steel powder bed at the interface between the support and the finished part. The added carbon reduces the corrosion resistance of the 316L. This allows full fusion of the support material to provide heat transfer and mechanical support during printing, while allowing the supports to etch preferentially by electrolytic etching. This causes the finished part to etch or break free from the supports without any need for machining, simplifying post-processing.

Introduction

Laser Powder Bed Fusion (LPBF) is an Additive Manufacturing (AM) technique that forms 3-dimensional designs by selectively fusing powder one layer at a time with a laser [1]. The process allows for internal voids, curves, and other geometries that are costly or impossible to produce with traditional casting and machining processes. This gives designers flexibility to produce parts with unprecedented complexity, and customizability [2].

In LPBF of metal, parts require sufficient support not only to hold up overhanging features, but also to resist shrinkage deformation [3]. They also provide an critical heat conduit to cool the melt pools [1]. The geometry and placement of supports is a critical aspect of the AM process [4, 5]. In LPBF, supports are welded to both the build plate and the finished part, making support removal a multi-step process. For robust support systems, as shown in Figure 1, parts are generally heat treated to relieve stress, then cut away from the build plate with a band saw or wire EDM and machined with a mill or ground by hand to remove the remaining supports. Multi-step post processing of metal LPBF parts reduces efficiency and may require over-design with sacrificial material to allow for support removal [6, 7]. Polymer PBF often avoids deformation by maintaining the bed above the crystallization temperature [8]. Vora, et al. showed how a similar benefit could be obtained in metal LPBF using in situ alloying to locally create a eutectic composition [9].

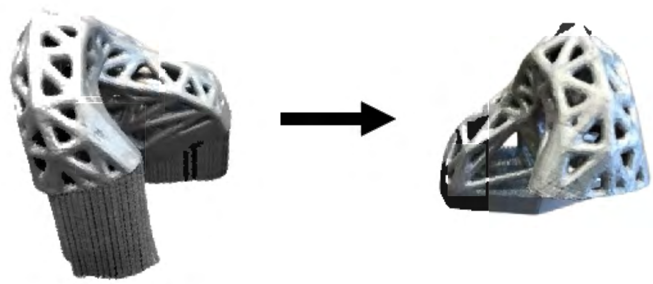


Figure 1. Complex design formed with Steel by LPBF. Extensive support structures such as these require multi-step post processing.

Meanwhile, some AM processes, such as plastic filament printing allow for the use of soluble support material. These dissolvable supports allow for delicate and intricate features, including cantilevers, horizontal bores, and long spans without concern for damage during support removal [10]. Dissolvable supports decrease the fabrication time and cost as post-processing is simplified by removing machining requirements [11] [12].

Wei et al showed that similar benefits could be obtained in LPBF by using a weak secondary material for support. However, this method requires a set of high precision vacuum and deposition nozzles to selectively remove material from the print bed, then deposit a secondary material where supports will be formed [5]. This method adds significant time to the print process and reduces the heat transfer capacity of the supports [5]. Other metal support removal methods proposed by Lefky et al. and Hildreth et al. require the addition of a sacrificial shell that is uniformly corroded away from the entire part [7, 13]. These methods reduce the resolution of negative features attainable by LPBF and increase the number of post-processing steps by adding a carburizing period.

This paper explores the effects of adding carbon as a corrosion-inducing agent to support material in a stainless steel (grade 316L) powder bed, then applying an electrolytic etch that has minimal influence on SS 316L but causes significant corrosion of the modified material. Electrochemical machining (ECM) takes advantage of the chemistry and electrical potentials of a work piece to precisely add or remove material using plating or etching fluids [14, 15]; ECM and its variants are the topics of hundreds of research papers annually [16], which provides excellent literature support and background for electrochemical support removal.

Several groups have shown that secondary materials can be precisely added to the LPBF bed using inkjet technology [17-20]. Using this approach, local additions of sensitizing agents to the support material could be used to create a region that is preferentially etched to free the completed part, reducing or possibly eliminating mechanical machining or the need to corrode a shell around the entire part (Figure 2).

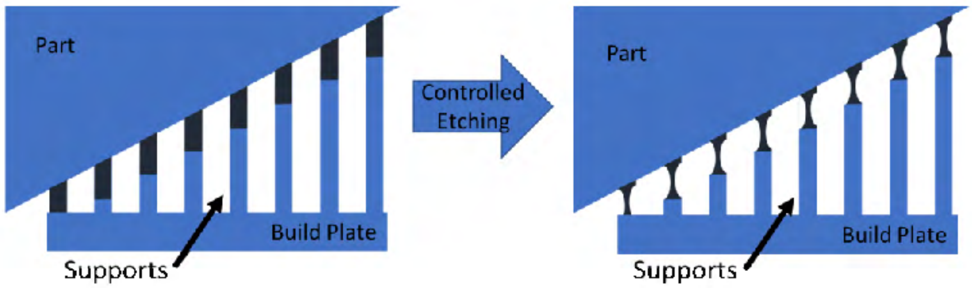


Figure 2. Proposed method of support removal by electrolytic etching.

Methods

Materials and Fabrication

Parts were fabricated using a Concept Laser GmbH (Lichtenfels, Germany) M2 Cusing multi-laser LPBF machine. Material stock was 316L stainless steel powder (CL 20ES, Concept Laser GmbH) with particles ranging in size from 15 µm to 45 µm. Layer thickness was 50 µm. The sensitizing agent was added to the final 10 support layers of the treated samples. Doping was accomplished by attaching a piezoelectric atomizer or 'mister' integrated with the LPBF coater blade as shown in Figure 3. This approach dopes a strip of the powder for the layers where it is activated. While this does not provide the spatial control of inkjet printing, it simulates the resulting carbon deposition and was more readily integrated into the commercial system.

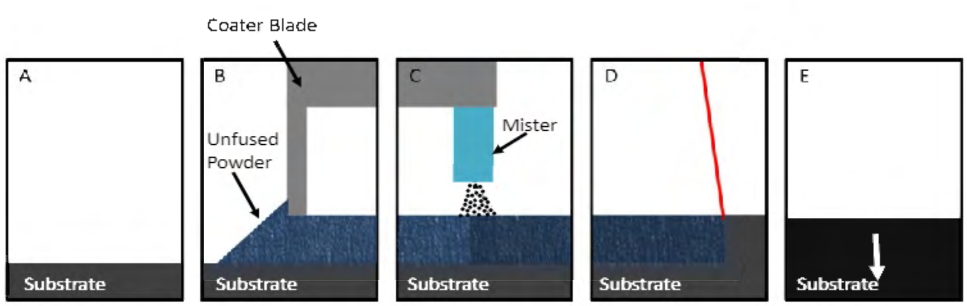


Figure 3. Proposed mechanism of precisely depositing the sensitizing agent on the powder bed to cause corrosion of the support material. A) A flat substrate is prepared by machining or spreading previous powder layers. B) The coater blade in the LPBF machine spreads a new layer of powder.

C) Deposition device attached to the coater blade deposits the sensitizing agent. D) The laser fuses material as controlled by a 3D model. E) The build plate is lowered to allow the next layer to spread. Note that for the current experiment, a piezoelectric atomizer was used to deposit sensitizing agent in place of inkjet printheads.

Etch Rate Comparison

The relative etch rates of doped and undoped regions were measured using sample two blocks doped with the carbon black sensitizing agent in 3 separate regions as illustrated in Figure 4. One block was heat treated at 700 °C for 10 minutes to sensitize the steel with added carbon, while the other was tested as fabricated. The blocks were ground down to 1200f grit using silicon carbide grinding paper with a manual polisher to get a smooth surface.

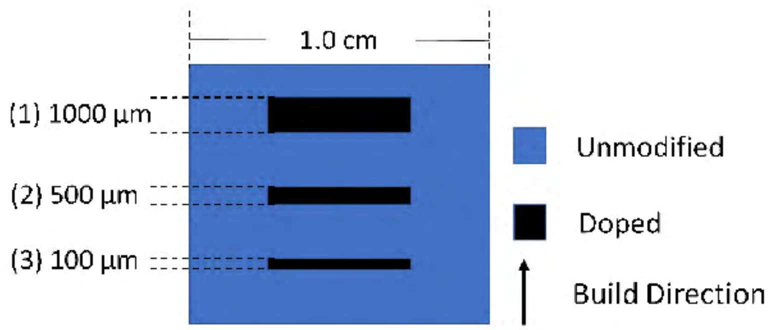


Figure 4. Sample block used to test the influence on doped layer thickness on etching rate. The direction of coater movement and dopant spreading is perpendicular to the sample as shown (into the page).

They were then etched in a 10% Oxalic acid solution to rapidly attack grain boundaries in the sensitized region, while slowly affecting unmodified SS 316L [21, 22]. Each block was submerged in the acid and attached to an anode with 15V potential for 15 minutes. After etching, the blocks were imaged using a Keyence VHX-7000 Digital Microscope, with a surface profile recorded for each block using the z-stack profilometer feature of the microscope at 400X magnification.

Support Removal Demonstration

A series of 3 samples with various support types and a porous "Y" structure were formed with 2 replicates. Supports use either line or solid type parameters, summarized in Table 1, with the geometry shown in Figure 5. The Line, Contour, and Hybrid supports attached to their respective parts by 0.1 mm teeth spaced every 1.5 mm. The Tree supports attached with fifteen 0.3 mm diameter branches spaced every 1.5 mm. The Point supports were 0.2 mm diameter and spaced every 3.0 mm. Complete documentation of advanced support parameters is recorded in Appendix C. The dimensions of each sample were measured, and all were found to be within 0.5%. The entire build was heat treated at 700 °C for 10 minutes to sensitize the steel. The samples with Tree type supports began to deform after several layers due to thermal stress, so they were aborted mid-print but the partially built samples were still tested with the other samples.

Table 1. Scan Parameters used to form different support types and bulk samples.

Parameter	*Type*	*Power (W)*	*Velocity (mm/s)*	*Spot Size (um)*	*Scan Spacing (um)*
Bulk	N/A	200	980	130	75
Solid	Point, Tree, Hybrid	370	1350	130	90
Line	Line, Contour	270	1200	50	N/A

For electrolytic support removal, the build plate with parts and supports attached was inverted and etched in an oxalic acid bath with +15V potential for 200 minutes as shown in Figure 5. After etching, each sample was removed in pure tension by an Instron 3400 Single Column Series tensile testing machine. Because support dimensions were unknown after etching, only total load to remove the parts was measured for comparison between doped and undoped supports.

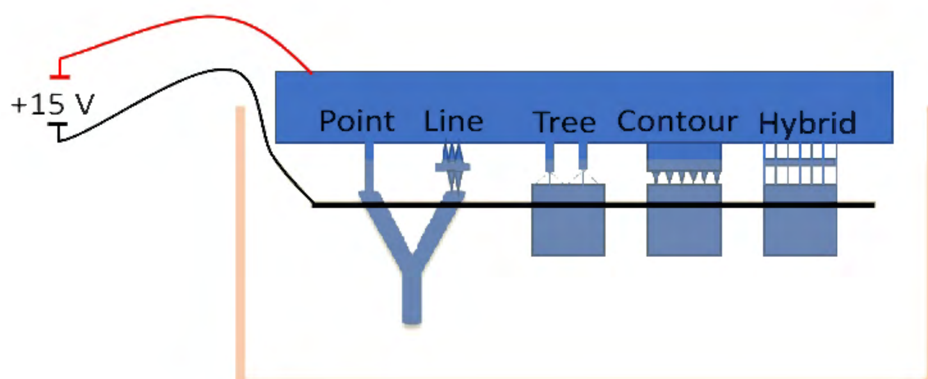


Figure 5. Diagram of experimental build plate with supports inverted in an electrolyte bath for electrolytic etching.

Results and Discussion

Sensitization of Doped Regions

Etching created distinct grooves (up to 100 µm deep) in the doped regions of the test blocks, while the unmodified material maintained a flat profile. Heat treatment significantly increased the sensitization of the steel, as proven by grooves 2x deeper etching in the heat-treated sample than the as-fabricated sample (Figure 6b). The same heat treatment was therefore applied to supported parts in proceeding experiments. It was also observed that there was not a strong relationship between the thickness of the doped region and the etched groove depth, indicating that as few as 5 layers of the support material needs to be doped for preferential etching to occur (see Figure 6).

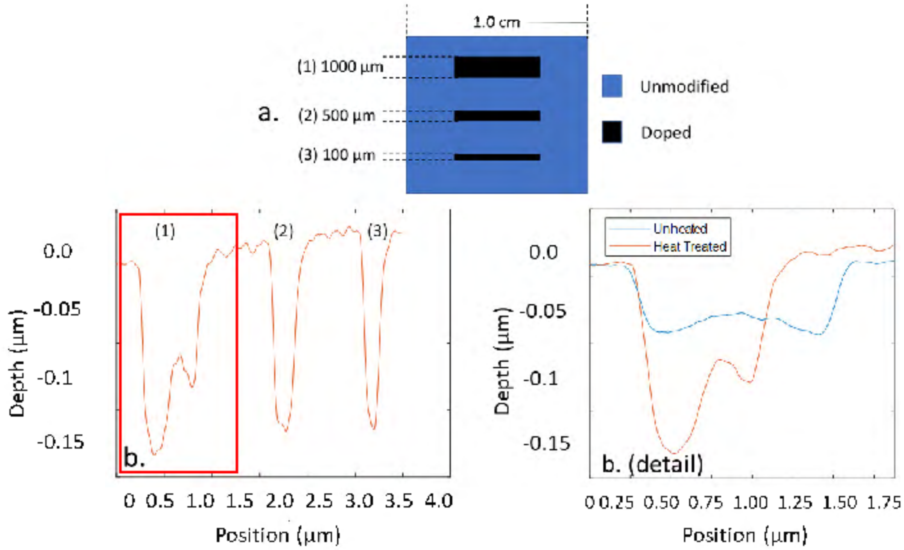


Figure 6. a) Geometry of experimental blocks used for validation. Region 1 is 1.0 mm wide, Region 2 is 0.5 mm wide, and Region 3 is 0.1 mm wide. b) Groove depth of sensitized regions of varying widths after 15 minutes of etching. detail) Groove depth profile for 1.0 mm wide doped region with and without heat treatment after 15 minutes of etching.

Support Strength

A graphical summary of the force required to remove each support type is shown in Figure 7. Sensitization treatment reduced the force required to remove supports in every case, but the change was most pronounced for the Tree and Contour types where the force required to remove parts from their supports was reduced by over 90%. The sensitized sample with the Tree supports separated while attaching the grip for the tensile tester, so the force required to remove it was negligible. No comparison is provided for the Point supports because both the doped and undoped supports separated due to etching, making any comparison trivial. Literature shows that the doped material has increased tensile strength [23]. Thus even the Line supports must have had reduced surface area in the sensitized supports to break with lower overall load than the unsensitized control.

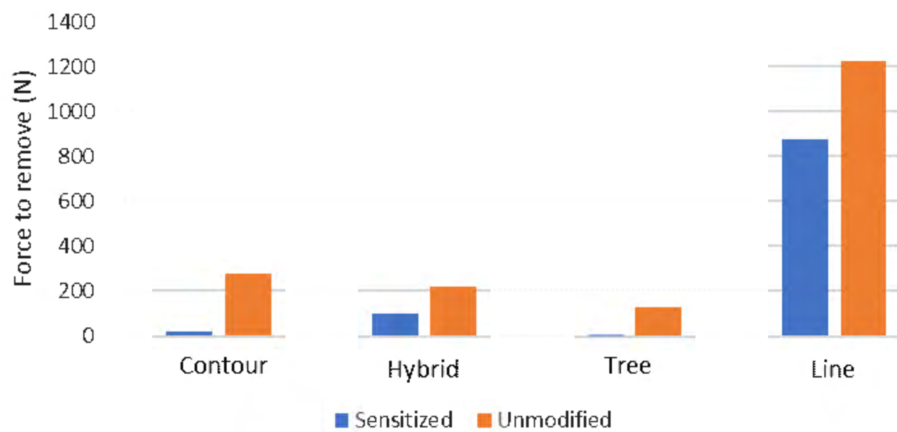


Figure 7. Force required to remove supports, sorted by type and treatment.

Another observation from tensile testing is that the sensitized supports fractured at a predictable location through the doped layers, while the unmodified supports yielded in a ductile way and broke in unpredictable locations, as shown in Figure 8. These failure modes were expected based on previous research showing fusion of mixed-grade steels [24]. These results suggest that this material system could also work without etching if the parts can support the force required to remove them by simple tension.

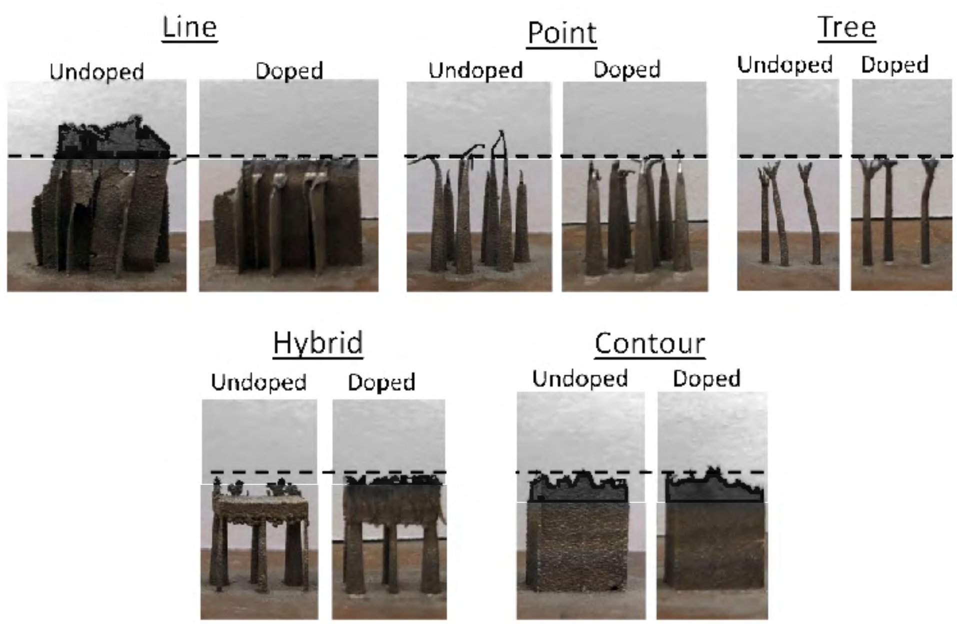


Figure 8. Ductile failure of supports formed by unmodified material and brittle fracture of doped supports for each support type.

Geometry

One problem with using corrosion mechanisms to remove metal samples from their supports is that submerging either the finished parts or the build plate in an etching fluid results in material removal from any submerged surface. This was a challenge of the current experiment. Although SS 316L is resistant to macro etching in oxalic acid, the overall dimensions of the supported parts were reduced uniformly by 0.25 mm due to their full submersion and long exposure to the electric potential. This could be reduced by optimizing the potential to maximize the contrast in etching rate between the doped and undoped regions as well as modifying the support parameters to minimize the thickness of the samples at the etch region.

General etching of the samples becomes a more obvious problem upon examination of the porous Y structures as in Figure 9. Both Y structures were reduced to thin delicate members during the etching process, despite being fabricated as robust members. If this procedure were used to avoid deforming delicate features during support removal, the integrity of those delicate features could be compromised by exposure to the etching process.

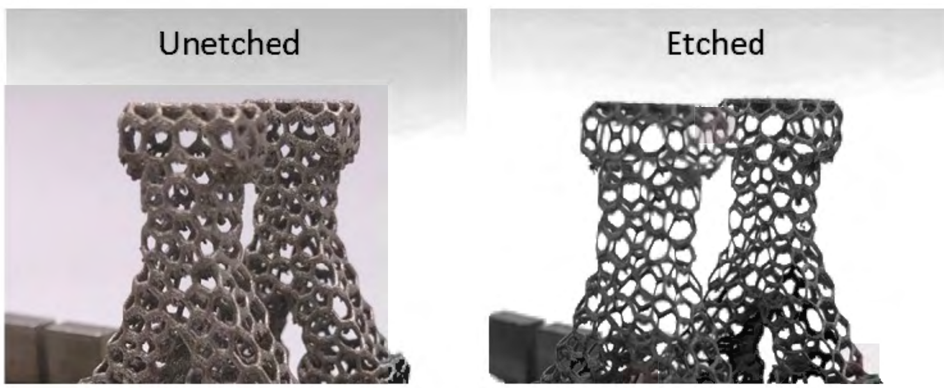


Figure 9. Comparison between unetched and etched samples, both after heat treatment. The Y structure obviously contains thinner members after etching, which is indicative of the change in geometry due to etching.

As a simple illustration, a second experimental build was performed with similar support types. In the second experiment, rather than inverting the build plate to suspend the parts in etching fluid, the build plate was coated with an insulating polymer and fully submerged in the etching fluid so the parts would not etch. The results, shown in Figure 11 and Figure 11, indicate that the modified etching configuration not only protects the structure of the printed parts, but also enhances etching in the supports, as less etchable surface was exposed to the electrolyte bath and the parts separated without any tension.

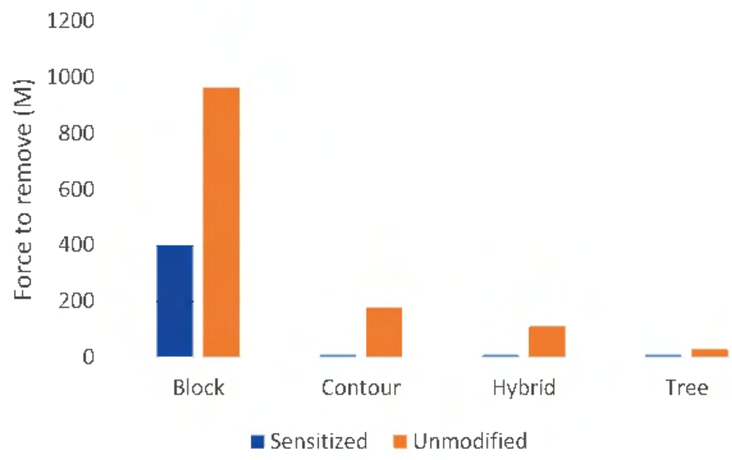


Figure 10. Force required to remove supports with the build plate submerged in the acid bath rather than the parts.

Other potential solutions to the problem of part etching during support removal are to use an etchant that more aggressively attacks the sensitized material for a shorter amount of time, such as the Al-7 etchant suggested by Nesbitt et al. for macro-etching of ferrous alloys [25] or to use a flexible cathode wire which could be strategically positioned near the supports to be removed.

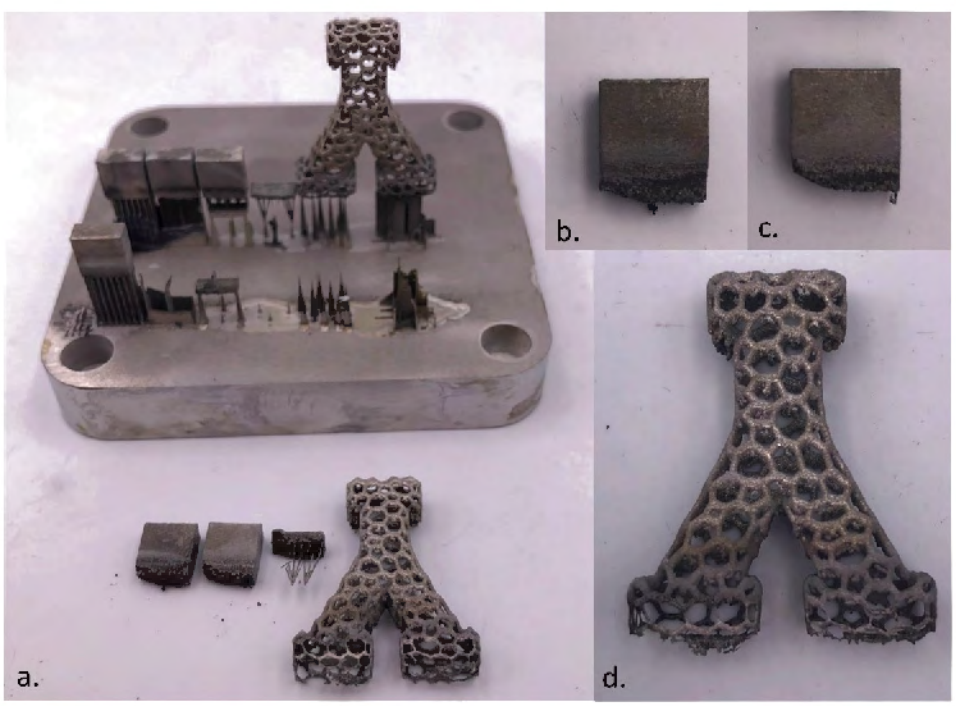


Figure 11. LPBF parts with sensitized supports released from the build plate during etching without need for any applied force.

Conclusions

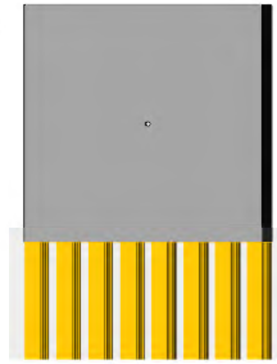
En-situ powder bed doping was employed to sensitize support structures for LPBF of stainless steel 316L. Despite using a gentle etchant, the dimensions of the product were altered by the etching process. However, the sensitized supports demonstrated a predictable fracture location when pulled in tension, unlike unmodified supports which yield and break unpredictably. Etching also reduced the dimensions of the sensitized supports sufficiently to decrease the fracture load by over 90% for certain support types. Overall, this method of forming easily removable supports by LPBF is plausible, but additional work will need to be done to improve the etching process so that the dimensions of the product are not affected.

Advanced Parameters used to form Easy-To-Remove Supports

Unless indicated, other advanced support options were not applied.

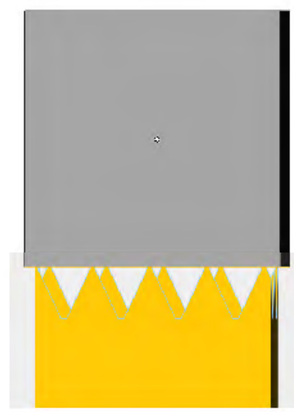
Point

Setting	*Dimension*
X, Y, Z offset	0, 0 ,0 mm
Fragmentation	
X, Y Interval	0.5, 0.5 mm
Separation Width	0.5 mm



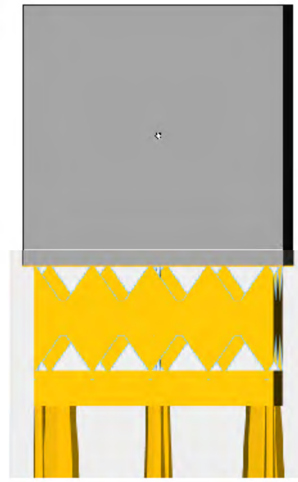
Contour

Setting	*Dimension*
X, Y, Z offset	0.3, 0.3, 0 mm
Teeth	
Upper	
Height	0.5 mm
Top length	0.5 mm
Base length	0.5 mm
Base Interval	0.5 mm
Lower	None



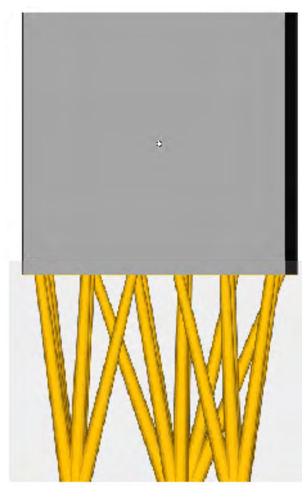
Hybrid

Setting	*Dimension*
X, Y, Z offset	0.3, 0.3, 0 mm
Teeth	
Upper	
Height	1.5 mm
Top length	0.1 mm
Base length	1.5 mm
Base Interval	0.2 mm
Lower	
Height	1.5 mm
Top length	0.1 mm
Base length	1.5 mm
Base Interval	0.2 mm
Middle Plate	1.0 mm
Cone Contact	0.5 mm



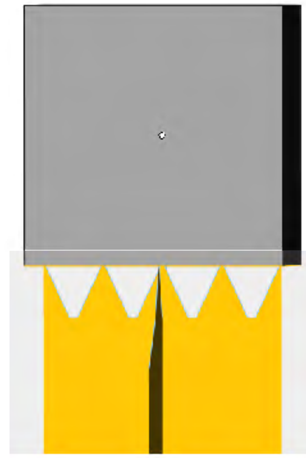
Tree

Setting	*Dimension*
X, Y, Z offset	0.3, 0.3, 0 mm
Trunk	
Top Diameter	0.5 mm
Bottom Diameter	0.8 mm
Branch	
Top Diameter	0.3 mm
Bottom Diameter	0.5 mm
Max Branches per Trunk	7



Line

Setting	*Dimension*
X, Y, Z offset	0.3, 0.3, 0 mm
Teeth	
Upper	
Height	0.5 mm
Top length	0.5 mm
Base length	0.5 mm
Base Interval	0.5 mm
Lower	None
Cross Line Length	6.0 mm
Cross Line Teeth	
Height	1.5 mm
Top length	0.1 mm
Base Length	1.5 mm



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