MICA Freeform vs Selective Laser Melting

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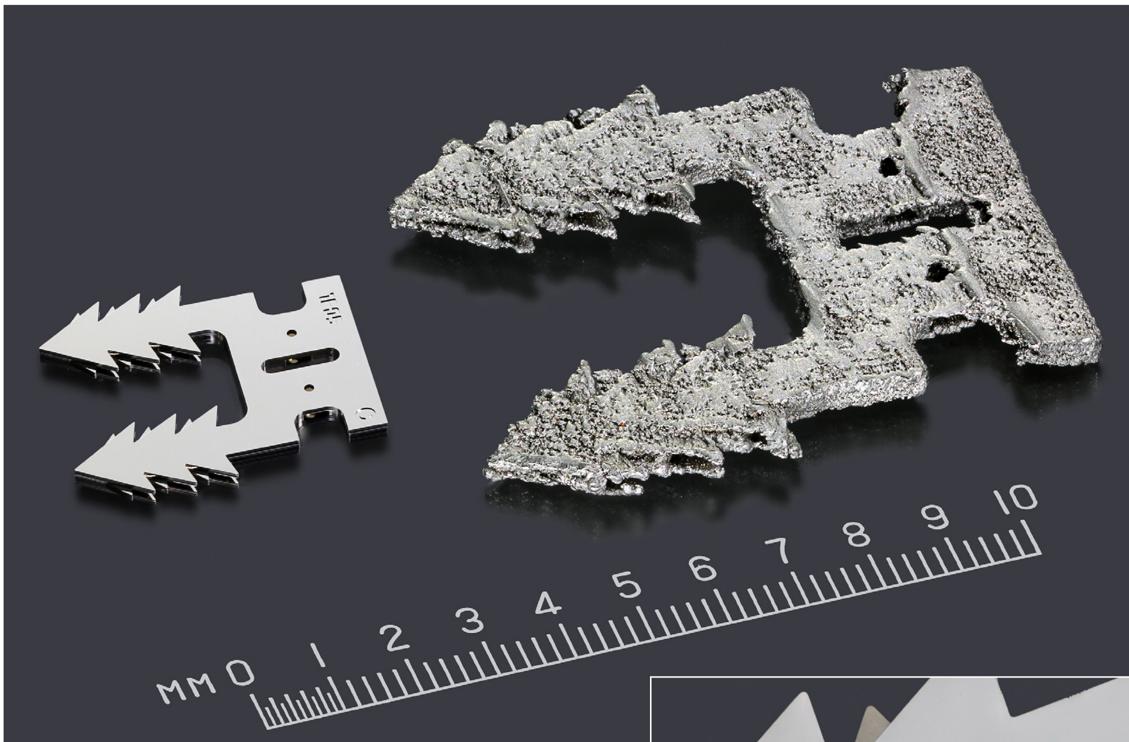

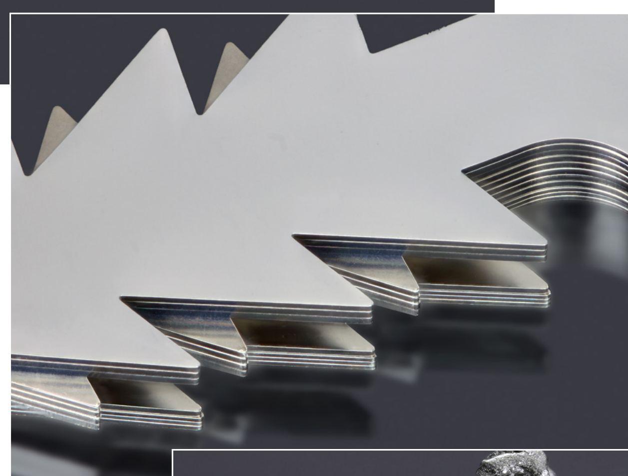

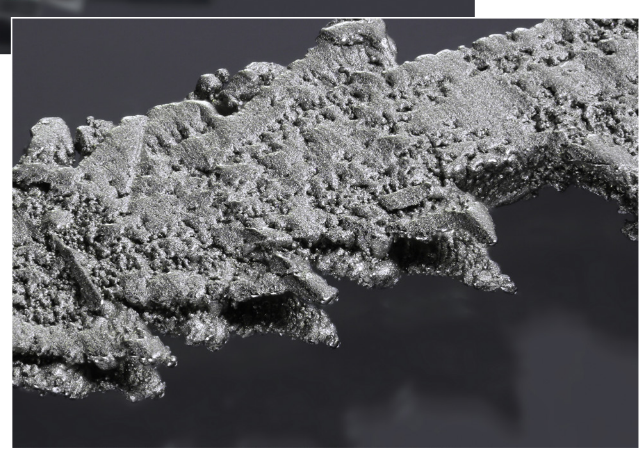

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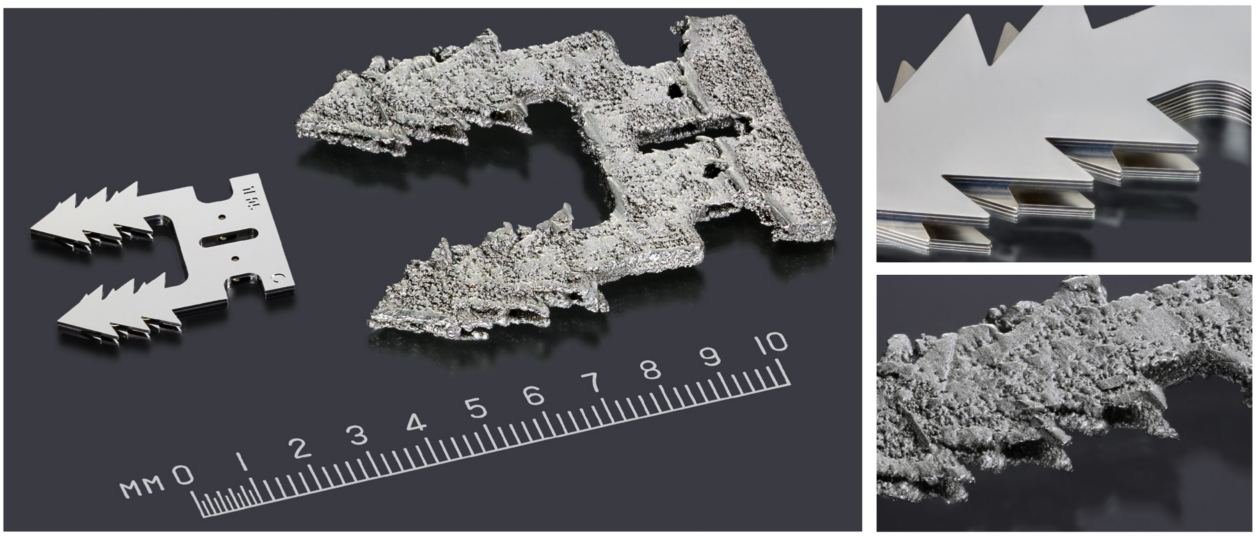

Optical image of a medical staple produced by MICA Freeform (left), and an enlarged (to allow fabrication) staple produced by the Concept Laser Mlab cusing SLM system.

Introduction

In the past few years, additive manufacturing (AM), or 3D printing of functional end-use parts has grown rapidly. While polymers are desirable for some parts, many applications require metals for higher strength or hardness. There is a growing trend for micro metal parts for the use in aerospace, semiconductor and medical applications. The drive to miniaturization for these parts has pushed conventional micro-machining to its limits in size and precision, therefore bolstering interest for new micro additive manufacturing technologies. In this paper, two AM processes for fabricating precision metal parts measuring millimeters in overall size will be reviewed: MICA Freeform and selective laser melting (SLM). Similar to other AM technologies, these processes use successive layers to create 3-dimensional parts. While both AM processes produce functional, metal parts, MICA Freeform and SLM employ dramatically different approaches and differ greatly in performance and capabilities.

MICA Freeform is used for the mass production of millimeter-scale metal parts with micron-size features. The process, available exclusively from Microfabrica Inc. of Van Nuys, CA, routinely prints millions of parts each year. MICA Freeform can also fabricate functional "printed mechanisms" comprising of multiple moving parts, with no assembly required. SLM is a process that has evolved from selective laser sintering (SLS), one of the earliest AM processes. Whereas SLS sinters metal powder particles together using laser energy—leaving significant porosity and typically requiring infiltration with another metal—SLM completely melts the particles, yielding parts that are denser than SLS, resulting in better mechanical properties. Companies offering SLS and SLM systems include Concept Laser, 3D Systems, EOS, 3D MicroPrint GmbH, and Renishaw. The Mlab cusing system made by Concept Laser—a machine intended for small, detailed parts—will be used as a basis of comparison; other companies' systems have similar, or less favorable, specifications. There are other direct metal AM processes available, in particular the electron beam melting (EBM) process of Arcam, the LENS process of Optomec, and the three-dimensional printing (3DP) process of ExOne. However, parts produced with these processes tend to have larger features and poorer surface finishes than those made with SLS and especially, with SLM. Moreover, parts made with 3DP are not fully dense and require infiltration. 3D MicroPrint has a micro laser sintering process using smaller particles, thinner layers, and a smaller laser spot but information on its process was limited at the time this paper was written.

MICA Freeform. Analogous to semiconductor fabrication techniques, MICA Freeform is performed in a cleanroom. It follows three primary steps for each layer. First, a fully-dense structural metal is electrodeposited at low temperature and with low stress onto a substrate in selected regions corresponding to a cross section of the part. The metal is deposited through apertures in a photoresist patterned using a sub-micron resolution photomask, a method borrowed from the semiconductor industry. After removal of the photoresist, a sacrificial metal is blanket-electrodeposited over the structural metal. Finally, both metals are planarized using a proprietary technique to yield a layer that is extremely flat, planar, and of accurate thickness. The three steps are then repeated for all layers required, after which a chemical bath is used to dissolve the sacrificial metal, freeing the parts (which may number in the thousands).

SLM. The SLM process involves spreading metal particles typically 10-50 µm in size over a substrate to form a layer typically 10-100 µm thick. Next, the focused, near-infrared beam of a fiber laser is directed, based on the part geometry, onto the surface of the layer using scanning mirrors, defining the desired part cross section. The absorbed energy melts the particles in a region surrounding the laser spot (the "melt pool"). Upon rapidly cooling, these fuse together to form solid metal and bond to the previously-formed layer. The powder spreading and melting steps are then repeated for all layers required, after which unfused powder is removed. Finally, anchor structures, added to the part design to reduce distortion caused by residual stress, are removed (e.g., by traditional machining techniques).

Comparison Between MICA Freeform and SLM

While both manufacturing processes use layers to create metal parts, MICA Freeform and SLM are very different with respect to how the metal layers are formed. With MICA Freeform, atomic-level deposition through patterned photoresist provides a layer's 2-D geometry, and planarization defines its thickness. With SLM, powder is melted locally to define the 2-D geometry, and layer thickness is determined by the thickness of the powder layer and the volume change occurring when fusing the powder. Moreover, with MICA Freeform, metal is deposited simultaneously over the entire layer—a parallel process—while with SLM, metal is fused one region at a time as the laser beam moves—a serial process. Given these differences, each process has intrinsic advantages and disadvantages. The performance and capabilities of the two processes will be compared to help determine the best process to manufacture a given part.

Layer thickness. Layer thickness has a major impact on several performance parameters: minimum feature size, accuracy along the Z (layer stacking) axis, surface finish, and vertical build rate. Thinner layers normally decrease build rate, but increases the resolution in the Z direction. MICA Freeform uses atomic-level electrodeposition to deposit metal, so layer thickness is limited primarily by the tolerance to which layers can be planarized. With SLM, layer thickness is limited by the minimum size of the metal particles, and the ability to spread them thinly with the required density. The minimum thickness for MICA Freeform is 5 µm, while for SLM it is 15-20 µm.

Minimum feature size. In the X/Y (layer) plane, the minimum size of structural features (e.g., the minimum thickness for a vertical wall) is constrained for SLM by the size of the melt pool, which is determined by the laser spot size, thermal diffusion, and other factors. Typically minimum wall thickness is twice the melt pool diameter. Ultimately, even if the melt pool is made smaller, the size of the metal particles places a lower limit on the thickness of walls that can be formed with acceptable definition. With MICA Freeform, wall thickness is driven mostly by the ability to define apertures in photoresist sufficiently thick to deposit the required layer. The minimum feature size for MICA Freeform is 20 µm, while for SLM it is 200 µm.

Accuracy. Accuracy in the X/Y plane is determined for MICA Freeform by the accuracy of the photoresist pattern, which is a function of photomask tolerances (< ± 1 µm) and photoresist processing conditions. For SLM, X/Y accuracy is determined mostly by shrinkage and residual stress associated with the transition from loose powder into dense metal, and by static and dynamic positioning errors of the scanning mirrors. X/Y accuracies of ± 2 µm (with excellent repeatability) are typical of MICA Freeform, while ± 100 µm is the typical accuracy of SLM. SLM can be somewhat better for small parts, depending on geometry and build orientation.

Along Z, accuracy with MICA Freeform is determined entirely by the planarization process, which is capable of ±2 µm tolerances. With SLM, Z accuracy is affected by factors such as shrinkage, residual stress, and thickness of the powder layer. As a result, the Z accuracy for SLM is in the range of ± 125 µm for parts < 25 mm in height.

Surface finish. Surfaces not strictly horizontal or vertical in AM are characterized by "stairsteps"; this purely geometrical effect is exacerbated with thicker layers. Process factors such as layer misalignment, and sidewall roughness, flatness and perpendicularity can further compromise finish, most obviously on vertical walls, while other process factors can improve or reduce surface quality. In the case of MICA Freeform, layers are aligned to a tolerance of ± 1.5 µm, and sidewalls are very smooth (exactly reproducing those of the photoresist), flat, and close to perpendicular to the layer top/bottom. Lastly, the planarization process step renders the top and bottom of each layer extremely smooth (e.g., 0.8 µinch Ra). With SLM, the powdered feedstock results in a fundamental limit on surface quality. Metal particles on part surfaces can remain rounded and voids between surface particles can remain after fusing, contributing to a surface that is very rough at the microscale. Particles may also agglomerate, increasing their effective size, and may not melt enough to merge into the part but enough to bond, forming attached spheres. With respect to top/up-facing and bottom/down-facing surfaces, SLM typically achieves a finish of ~125 and ~300 µinches, respectively.

Net shape. Parts made with MICA Freeform normally require no manual post-processing to remove support material (this is chemically etched) or to improve accuracy or surface finish. However, anchors used in SLM must be removed manually, and for some applications, machining or polishing operations are further required. It should be noted that SLM part geometries that include internal features, complete anchor removal or secondary operations may not be achievable due to lack of access.

Multi-component mechanisms. MICA Freeform is commonly used to produce assemblies with multiple moving parts. This capability is enabled by the use of separate support material which fills the gaps between parts and is later chemically dissolved away. The excellent surface finish allows parts to move with little friction. SLM, by contrast, is limited in this ability due to the need to remove anchors and loose powder, and the relatively poor surface finish.

Mass production. Very high volume manufacturing of sub-millimeter sized parts is routine for MICA Freeform, and multiple wafers may be processed simultaneously in a cleanroom to meet production needs. Moreover, support removal is achieved through an automated batch process. By contrast, while it is possible to build many parts in an SLM machine, the vertical build rate is reduced. Moreover, anchors cannot be removed other than manually, one part at a time. For these reasons, SLM tends to be limited to prototyping and short run production.

Materials selection. The choice of metals in MICA Freeform is limited to those which can be electrodeposited with low stress and at reasonable rates, and for which there is a selectively-etchable sacrificial material. At present, the choices are nickel-cobalt, palladium, and rhodium. By contrast, SLM can in principal be used to build parts from any powdered metal (though refractory metals would be challenging). While the Mlab cusing typically uses stainless steel, other SLM machines work with titanium, aluminum, gold, cobalt-chromium alloy, nickel alloys, and maraging steel.

Part size. Parts and assemblies fabricated by MICA Freeform are normally limited to a height of 1 mm (taller parts can be made by stacking parts and welding). Parts are also limited in X/Y extents by the wafer size (currently 100 mm diameter). Thus, the process is generally used to make parts with volumes of 100 mm3 or smaller. The high volumetric build rate (e.g., 1 - 5 cm3/hr) and larger substrates used in SLM, on the other hand, enable taller and larger millimeter-scale parts to be produced (though not necessarily economically in volume).

Tooling and build time. MICA Freeform uses photomasks to pattern each layer of a part. Photomasks usually takes a few days to create and adds tooling cost to the initial MICA Freeform build. Conversely, SLM, like most AM processes, is driven directly by the part geometry file, so a part can start building within minutes of completing its design, and without additional expense. The build time for a part fabricated by MICA Freeform is several weeks while the build time for a part fabricated with SLM can be several hours.

Table 1 summarizes the comparison discussed above. Bold and italicized text signifies a relative advantage in making millimeter-scale parts.

	Microfabrica MICA Freeform	Concept Laser Mlab cusing SLM
Minimum layer thickness (µm)	***5***	15-20
Minimum X/Y plane feature size (µm)	***20***	200
Minimum Z axis feature size (µm)	***5***	15-20
X/Y accuracy (µm)	***± 2***	± 100
Z accuracy (µm)	***± 2***	± 125
Surface finish-layer top/bottom (µinch Ra)	***<0.8***	125-300
Particle size (µm)	***0.3×10^{-3} (electrodeposited atoms)***	10-30
Net shape (no finishing required)	***Yes***	No
Functional, multi-component mechanisms	***Yes***	Difficult/impossible
Support removal	***Chemical etching***	Manual
Mass production possible	***Yes***	No
Materials selection	Ni-Co, Pd, Rh	***Stainless steel, etc.***
Maximum part height (mm)	1	***80***
Build time	Weeks	***Hours***

Table 1. Summarized performance and capabilities of MICA Freeform and the Mlab cusing SLM system.

An immediate appreciation of some of the differences in process capability—in particular, the resolution/definition of the intended shape—can be realized from the optical images in Figs. 1-2, which depict a miniature medical tissue staple made with MICA Freeform, side-by-side with the same part (enlarged to allow fabrication) made with SLM. Figures 3-4 show scanning electron micrographs (SEM) of the same parts.

Figure 5 is an optical image of a millimeter-scale gear made with MICA Freeform (left) and a enlarged version of the same part made with SLM. As seen with the staple part, the relatively poor definition of SLM parts in this size range is apparent, especially in the region of the central locking hole that was designed with undercut features.

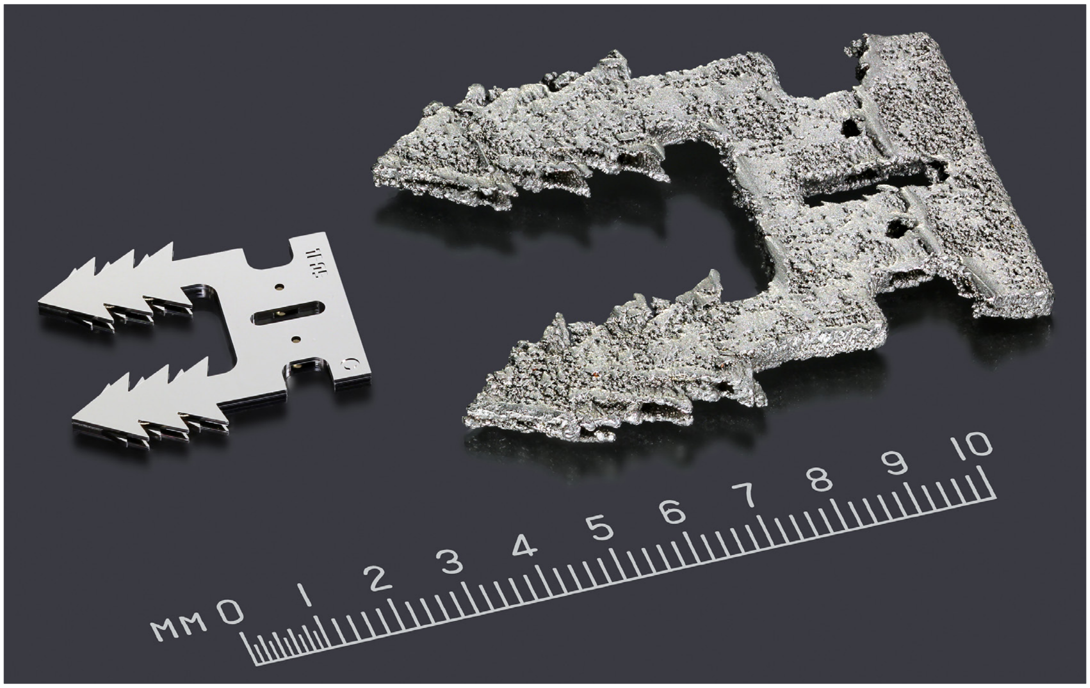

Fig. 1. Optical image of a medical staple produced by MICA Freeform (left), and enlarged staple produced by the Concept Laser Mlab cusing SLM system.

Fig. 2. Magnified optical image of the parts shown in Fig. 1.

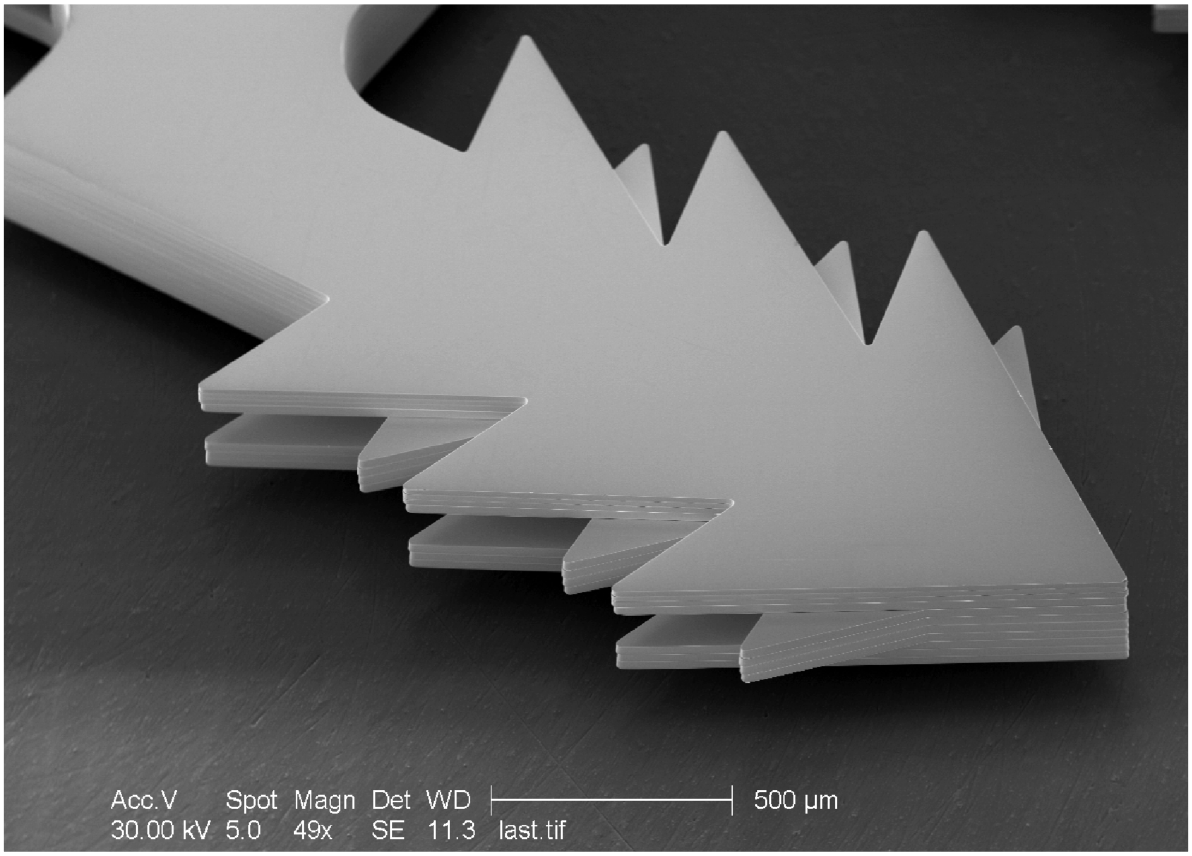

Fig. 3. SEM of the staple fabricated using MICA Freeform

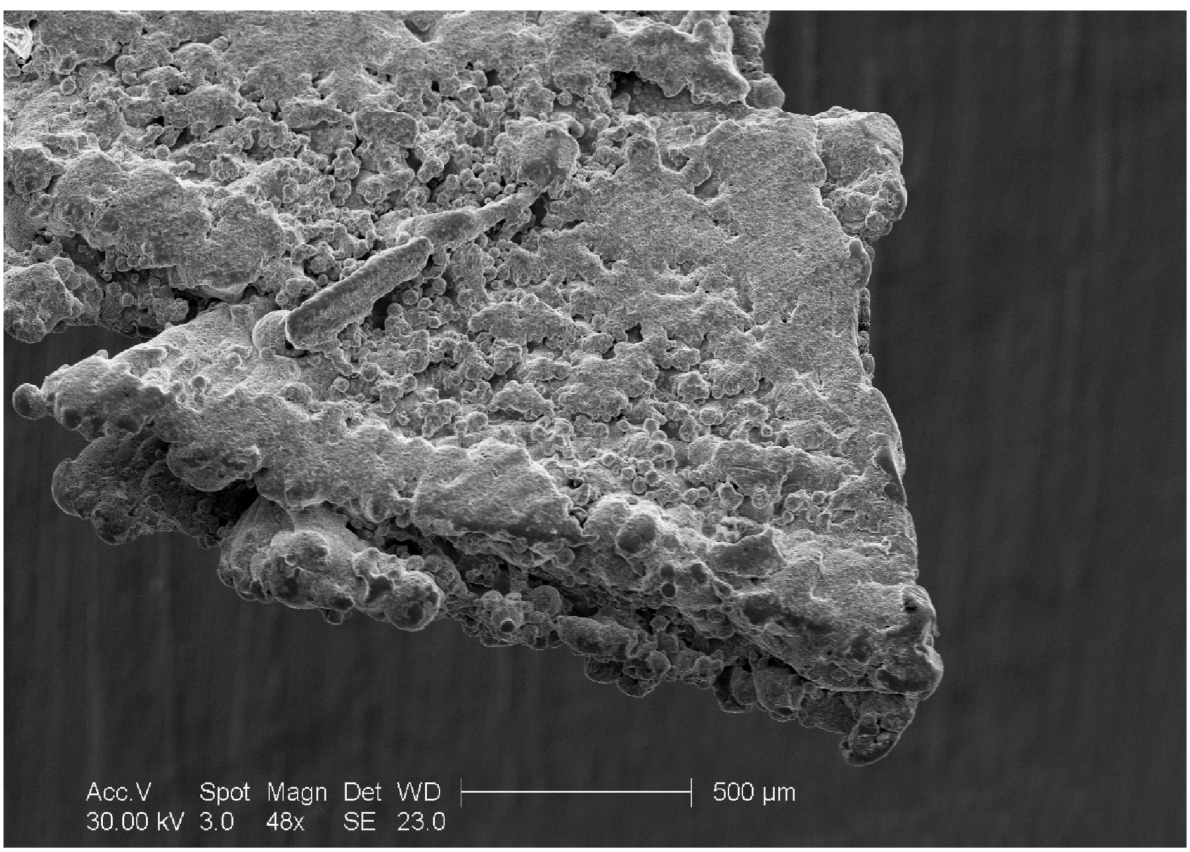

Fig. 4. SEM of the staple fabricated using SLM

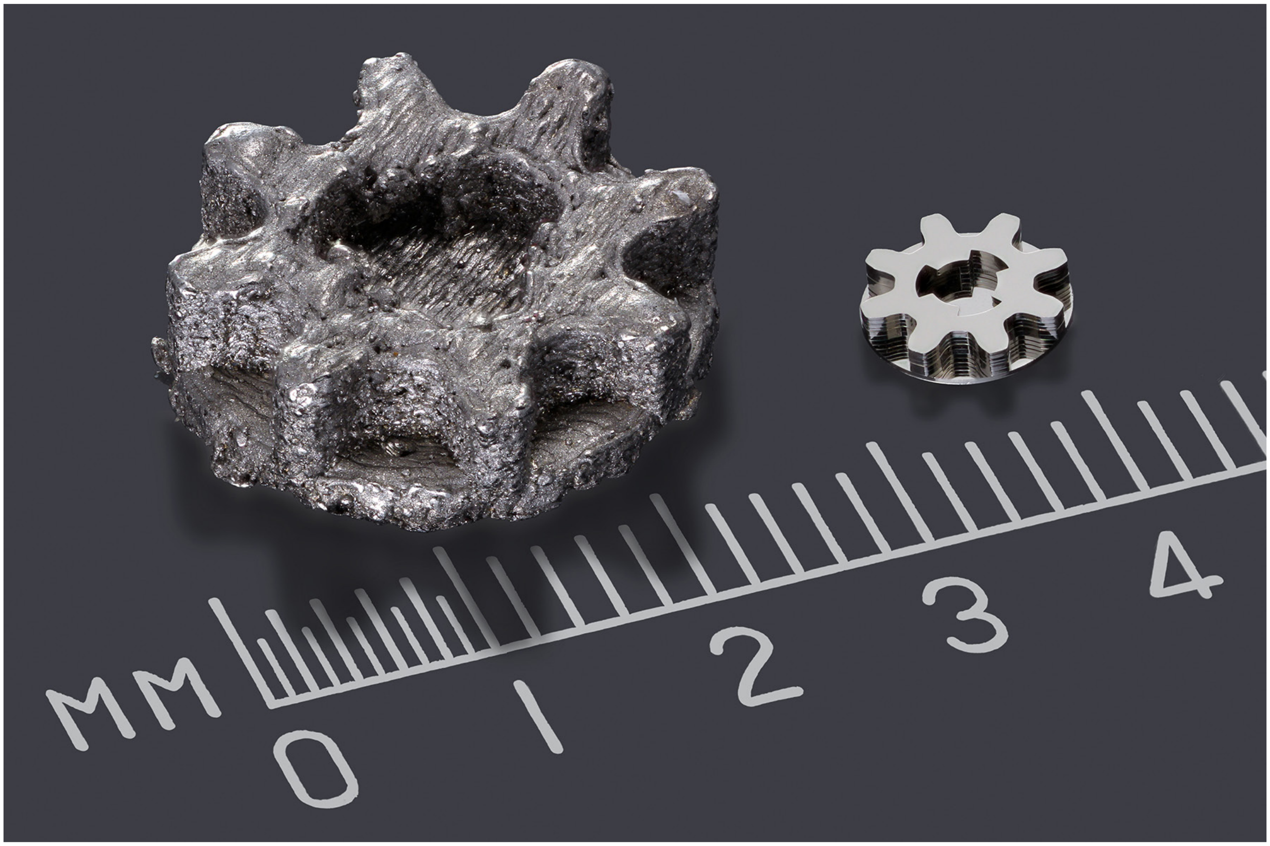

Fig. 5. Optical image of an enlarged SLM-produced gear (left) and a MICA Freeform produced gear.

Conclusions

We have analyzed the intrinsic performance and capabilities of two direct metal additive manufacturing technologies—MICA Freeform and Selective Laser Melting—in the context of producing parts with overall sizes of several millimeters, and illustrated some of the differences with images of sample parts. SLM offers a wider selection of materials and can fabricate larger parts quickly without any tooling. However, MICA Freeform is more capable of producing ultra-precise, net-shape, ready-to-use parts with extremely smooth surfaces and small, well-defined features. Moreover, MICA Freeform is able to repeatably produce such parts in very high volume, and also provides the ability to manufacture functional multi-component mechanisms that obviate the need for assembly. Both technologies have an important place in precision manufacturing. Engineers wishing to select the best process to manufacture a given part should consider the pros and cons of each technology in light of design and cost goals and the quantity required.

Notes

Data relating to MICA Freeform was obtained from Microfabrica Inc. Data relating to the Mlab cusing system was obtained from Concept Laser, discussions with a major U.S. service bureau using the Mlab cusing system, and from published documentation. Images are provided by Microfabrica Inc.

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