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Selective Laser Sintering of PA2200:

Effects of print parameters on density, accuracy, and surface roughness.

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Abstract

Additive manufacturing needs a broader selection of materials for part production. In order for the Los Alamos National Laboratory (LANL) to investigate new materials for selective laser sintering (SLS), this paper reviews research on the effect of print parameters on part density, accuracy, and surface roughness of polyamide 12 (PA12, PA2200). The literature review serves to enhance the understanding of how changing the laser powder, scan speed, etc. will affect the mechanical properties of a commercial powder. By doing so, this understanding will help the investigation of new materials for SLS.

Introduction

Current demands in the manufacturing industry require the ability to freely design products and increase their geometric complexity.[1] The developing field of additive manufacturing (AM) is continuing to show promise and appeal to these industry demands, as it circumvents conventional production problems by incorporating freedom of design, tool-less fabrication which allows shorter product development time, and complex product designs.[1]

There are multiple additive manufacturing techniques: fused deposition modeling (FDM), 3D-Printing (3DP), selective laser sintering (SLS), selective mask sintering (SMS), laminated object manufacturing (LOM), solid foil polymerization (SFP), stereolithography (SL), and finally laserjet chemical vapor deposition (LCVD).[1]

SLS, in particular, is a promising technique due to its ability to produce high complexity products with strong mechanical properties and good consistency. The technique is displayed below in Figure 1.

Figure 1: Three-step SLS process which involves, from the left, the rolling of the powder material across the bed, the laser sintering of the powder, and the lowering of the bed to allow the next layer to roll over the sintered layer.[2]

The first step in the process involves applying powder in layers into the area where the part will be built. The temperature of this powder is kept just below the material's melting point to allow full particle coalescence during laser sintering. A computer-designed model is inputted into the SLS machine, whereby the laser will melt the area per that design model. Finally, the powder bed is lowered down by the thickness of one layer, and the process is repeated until the part is complete. Then a cooling phase ensues, after which the part is retrieved from the machine.[2]

Though SLS has gained considerable interest, a limited selection of materials are available.[3] Investing in research of new materials is the current focus. SLS of polyamide materials are widespread across the additive manufacturing literature; Polyamide-12 (PA2200, Nylon-12) is widely used. PA2200's popularity can be attributed to its desirable list of properties: low melting temperature, low heat conductivity, large sintering window (distance between melting and crystallization temperatures), low melt viscosity, high surface tension, spherical particle shape, narrow particle size distribution, good flowability, and high packing density.[3]

This literature review focuses on PA2200, a PA-12 powder supplied by the company EOS. Some of the research reviewed will involve other PA-12 powders, but the reported results are transferable. The report will review how print parameters of the SLS process, specifically laser power, scan speed, energy density, part bed temperature, layer thickness, and print orientation, and the powder's inherent properties will affect the resulting part's density, accuracy, and surface roughness.

The primary reason for the limited selection of materials available to SLS is the lack of understanding of powder behavior and the relationship between print parameters and mechanical properties of end-parts.[3] This literature review serves to enhance the understanding of PA2200 for SLS processing, in the hopes to build a path towards printing new materials in the future.

Current State of the Technology

The mechanical properties of SLS parts vary greatly with the properties of the powder from which they were made, and vary with the process parameters used during the build. The effects of various process parameters on the resulting mechanical properties must be demonstrated.

Density of sintered parts by SLS on PA2200 powders increases with increasing energy density (ED). ED is defined as:

Equation 1:

$$ED\left(\frac{J}{mm^2}\right) = \frac{LP\ (W)}{SS\ (mm) * LS\ (\frac{mm}{s})},^{4}$$

where abbreviations are laser powder (LP), laser fill scan spacing (SS), and scan speed (LS). These parameters are inputted into the machine prior to the build.

However, at very high ED parameters, the density is found to decrease after a certain point. Furthermore, part density can be maximized when building in the 0° orientation, using Figure 2 to denote 0°.

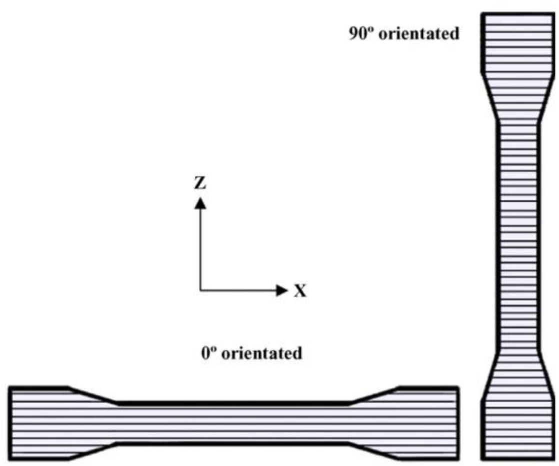

Figure 2: Part build orientations by B. Caulfield et al. The black lines indicate how the layers arrange in the part.[4]

These orientations were used to print the parts which showed the effect of ED on part density. Figure 3 below displays the results of B. Caulfield et al., who have found increasing ED produces parts with greater density.[4]

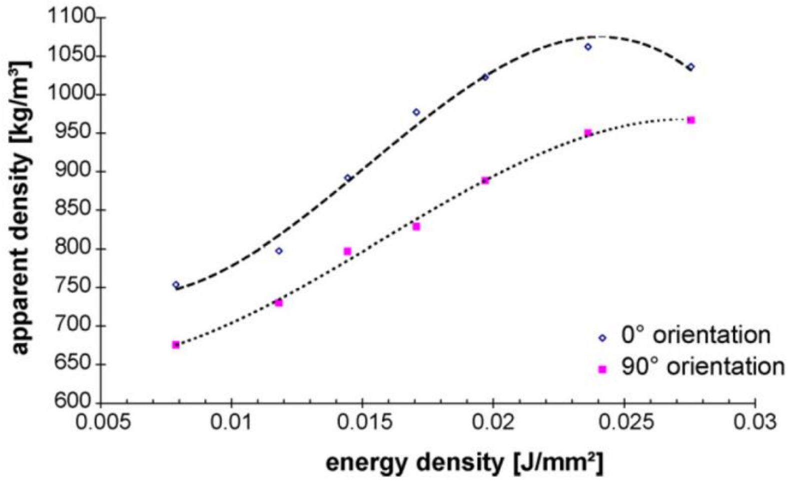

Figure 3: Comparing part density values between different build directions and varying ED values. An energy of 0.024 J/mm^2 will give highest part density built at a 0° orientation.[4]

The conclusion from the results in Figure 3 is that as ED increases, the part density tends to increase to a certain limit; too large of value for ED will diminish the part's density. This conclusion is further reinforced by another study, which qualitatively analyzed the effect of ED on part density. They found a medium ED produces the best part density based on SEM imaging.[5]

The conclusion from B. Caulfield et al. showing highest density is achieved in the 0° orientation is further supported by a study on porosity with varying print orientations. A part's porosity is inversely related to the part's density. The orientations used are displayed in the figure below.

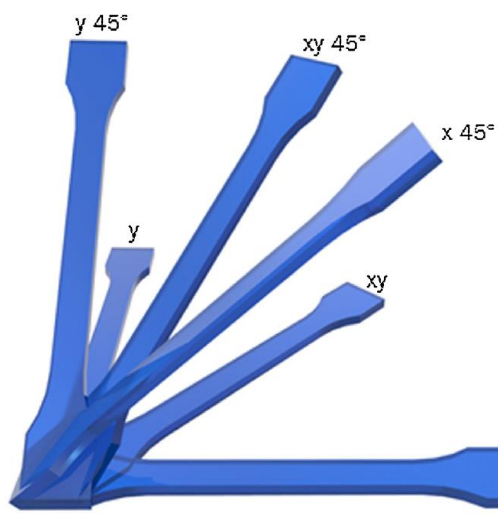

Figure 4: Print orientation of tensile specimens produced to analyze effect of print orientation on part porosity.[6]

The x-direction in this study is the same as the 0° direction in B. Caulfield's study, and the y-direction is the same as the 90° direction. The results are displayed in Table 1.

Table 1: Effect of print orientation on the internal porosity of parts using PA2200/carbon fiber composites.[6]

Build direction	Internal porosity (%) Average	Standard deviation
x	11.8	0.2
y	12.3	0.2
xy	15.9	0.7
x 45°	13.2	1.3
y 45°	11.4	1.3
xy 45°	12.3	1.7

The x- and the y 45° directions produce the lowest porosities in the resultant parts. As previously mentioned, this study reinforces the conclusion that density is maximized (minimized porosity) when print orientation is 0° according to Figure 2. It is desirable to achieve maximum density in sintered parts if strong mechanical properties are needed.

In a statistical study on PA2200, they found the best laser power/scan speed combination to achieve the highest possible part density. Low scan speeds of 39.5 mm/s and higher laser power of 3.72 W produced a 0.732 g/cm^3 part density. To build these parts, they introduced a new build method which alternated the scanning of each layer by the x- and y-directions. Essentially, the first layer is scanned in the x-direction, and the subsequent layer is scanned in the y-direction.[7]

With regard to the powder properties' effects on part density, Ziegelmeier et al. concluded the part's density is increased and part porosity is decreased when the SLS powders have greatest packing and flow efficiencies.[8]

Another affected property of parts produced via SLS is accuracy. Powder materials like PA2200 will exhibit shrinkage during the processing, resulting in undesired dimensions. Manufacturing accurate parts is imperative for additive manufacturing to become a commercialized, widespread technique. The effects of print parameters on accuracy are described.

The effects of ED and build orientation were investigated on the resulting part's accuracy, specifically the width and thickness.[4] Parts were built using PA-12 of the DuraForm family by 3D Systems. Build orientations were 0° and 90° (refer to Figure 2). The results for part width and thickness are shown in Figure 5 and 6, respectively.

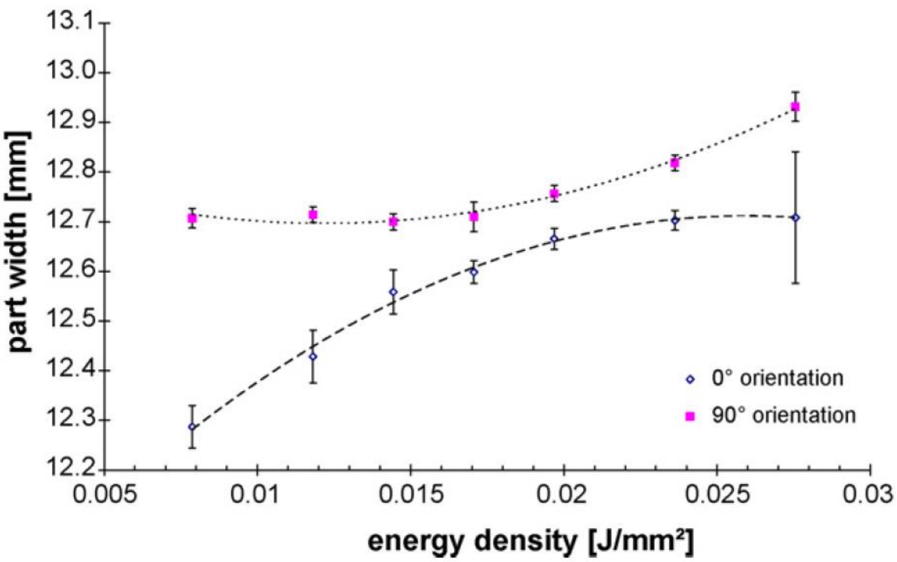

Figure 5: Effects of ED and print orientation on the part width. The desired part width here was 13 mm.[4]

All values are below the desired 13 mm value, and are likely due to part shrinkage during processing. The trend follows a decrease in part shrinkage with increasing ED, since the curves approach the desired 13 mm width with increasing ED. Also, shrinkage seems to be different among the orientations used, which is useful information. These results indicate that the computer model designs of these parts may need to overshoot the desired values if accuracy is important to achieve. Furthermore, more part accuracy data would enhance the ability to understand SLS processing behavior and would potentially help produce more accurate parts. The thickness of resulting parts had a different trend, as shown in Figure 6.

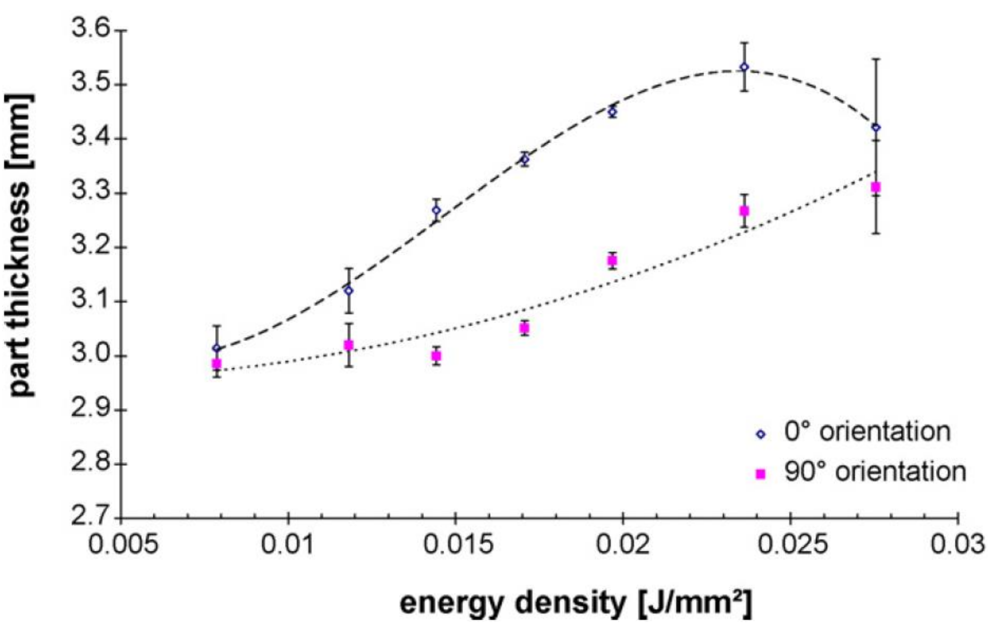

Figure 6: Effects of ED and print orientation on the part thickness. Desired thickness value here was set at 3 mm.[4]

Parts were more accurate with thickness. The 90° orientation was very accurate to 3 mm below 0.02 J/mm^2 energy densities. Interestingly, the thickness values rose with increasing ED regardless of print orientation.

As seen above with part width, warping (shrinking) of parts is a common problem encountered in part accuracy for SLS processes. A study specifically investigated the process parameter effects on warping of PA2200 and HDPE composites (50/50 w/w). They found a relationship to exist between process parameters and part warpage. Results are shown in Figures 8-11, in which all results are based on the analysis of warping at four distinct points shown in Figure 7.[9]

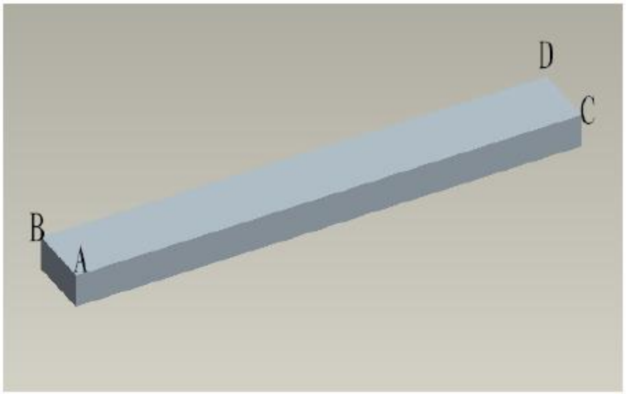

Figure 7: The computer model design for the parts built of PA2200/HDPE composite. Each of the points, A, B, C, and D, were analyzed for warpage.[9]

Using these points, the study provides a value for warping based on how far the part measurement at these points deviated from the model design. First analysis is on the relationship between warping height and preheat temperature of the part bed, Figure 8.[9]

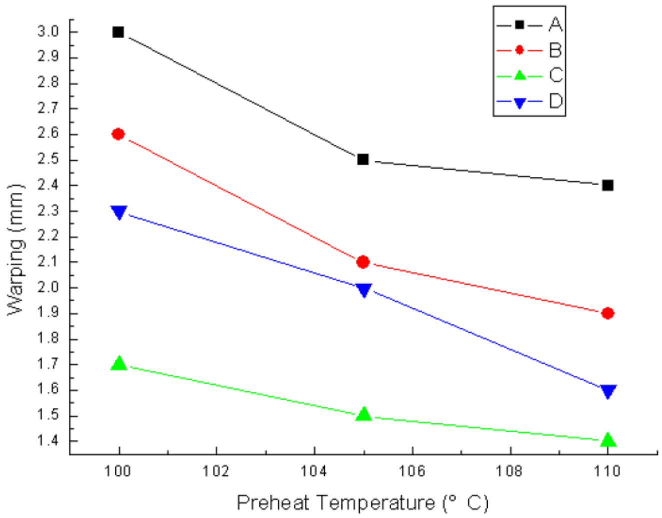

Figure 8: Effect of part bed temperature on the warping of an SLS part.[9]

The lowest warping was found at 110°C. This is at the melting temperature of HDPE. The data then supports the part bed temperature should be set as close to the melt temperature of your powder material as possible, to minimize warping of the sintered part. The warping is largest at point A, due to laser scanning beginning at point A and going towards B. This caused a thermal gradient to be greatest at point A, resulting in increased warping of the part.[9]

To obtain the relationship between scan speed and warping, all other parameters (part bed temperature, laser power, and single layer thickness) were kept constant while only varying the scan speed. Results are shown in Figure 9.[9]

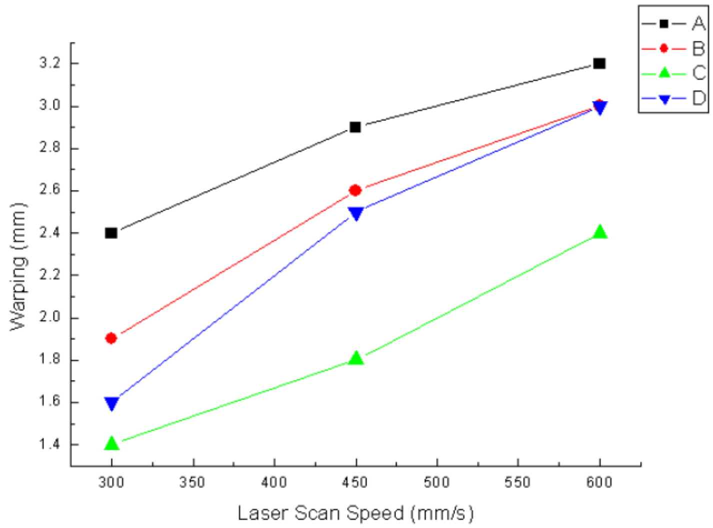

Figure 9: Effect of laser scan speed on the warping of a SLS part.[9]

The magnitude of warping increases with increasing scan speed. Increasing scan speed decreased ED values. From Figure 9, it can be concluded that as ED decreases, the magnitude of warping in the part increases. This conclusion supports the findings from Figure 5, which show part warping increasing with decreasing ED.[9]

Results of varying laser power are shown in Figure 10.

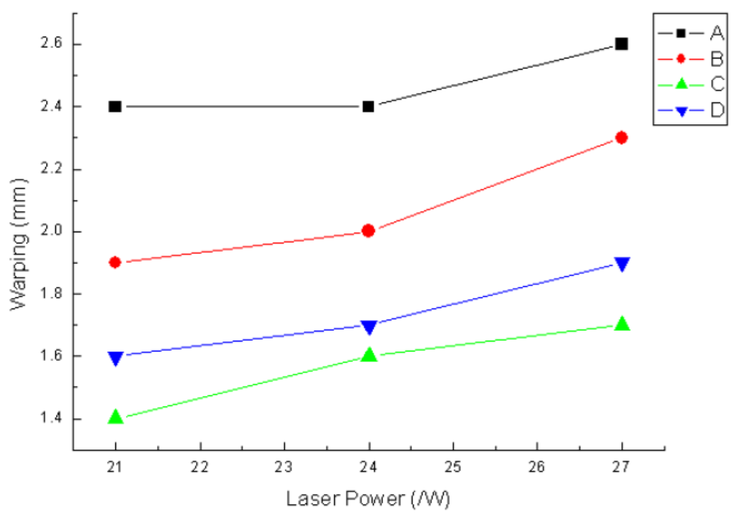

Figure 10: Effect of laser power on warping of sintered parts.[9]

From data in Figure 10, laser power does not have as great of an effect on warping as the other parameters analyzed in this study. Slightly more warping is found with increasing laser power. Increasing laser power increases ED. So, increasing shrinking is realized with increased ED. These findings interestingly conflict with the findings from Figure 5 and 9, showing a decrease in shrinking with increased ED.[9]

Results of varying sintering layer thickness are shown in Figure 11.

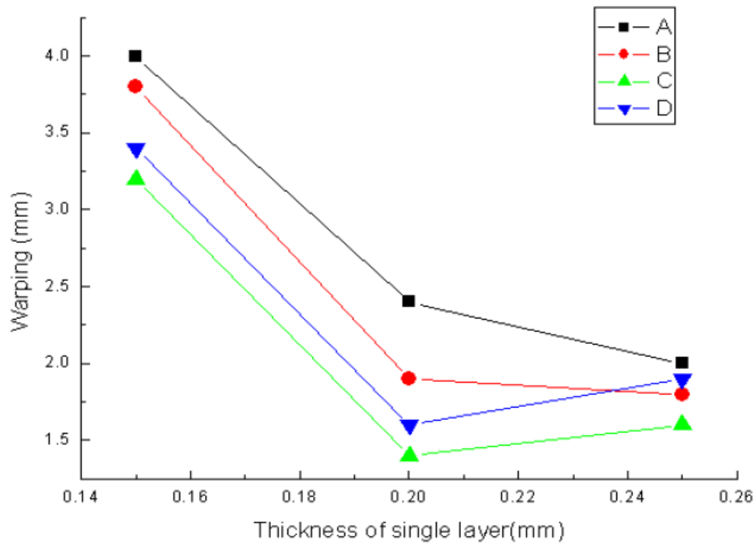

Figure 11: Effect of sintering layer thickness on part warping.[9]

The warping of sintered parts greatly reduced with increasing layer thickness. This is likely attributed to the thick powder layer not receiving as much energy from the laser to fully melt, thereby the thermal stress is reduced on the part leading to less warping. Increasing thickness of a single layer will likely reduce the mechanical properties of the final part, since the layers will not bond well. Although increasing layer thickness minimizes warping, it is undesirable to increase layer thickness because of the resulting poor mechanical properties of the part.[9]

For certain applications and customers, parts with rough surfaces are undesirable. It is then important to understand which parameters increase/decrease surface roughness of parts. From current literature, high scan speeds lead to rough surfaces versus lower scan speeds. These studies were performed on PA-12 of DuraForm from 3D Systems. Figure 12 shows SEM imaging of sintered part surfaces made with varying scan speeds and at a constant laser power.[10]

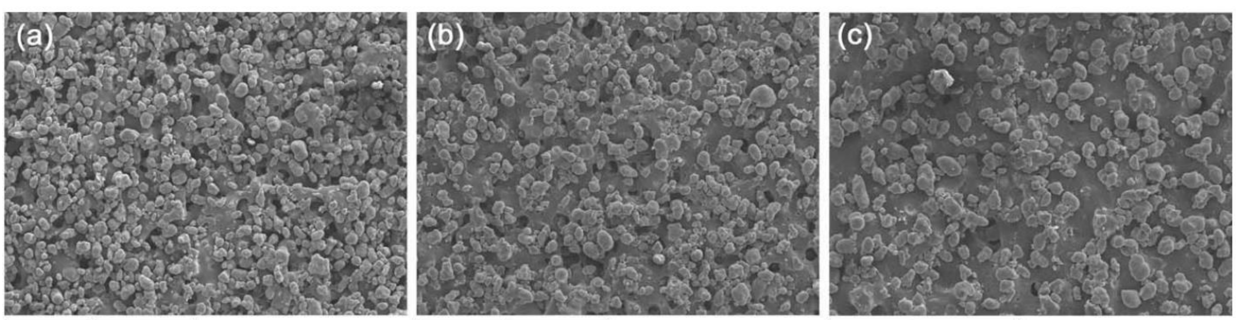

Figure 12: SEM imaging of SLS parts made using (a) 1600 mm/s, (b) 1200 mm/s, and (c) 800 mm/s scan speeds, while holding laser power at 5 W.[10]

According to Figure 12, the surfaces gradually become smoother as scan speeds are decreased. This same result is found with increasing the laser power from 3 W to 5 W and 7 W; scan speed was held at 1200 mm/s. As laser power increased, surfaces appeared smoother. With regard to energy density, the study concluded surfaces are rough at lower ED values. Furthermore, scan speed had greater effect and was easier to control part properties versus laser power.[10]

Another study performed similar investigations using the same powder material. Under 9 W laser powers, the surfaces appeared porous due to too low ED. As ED increased, the surface became smoother except when laser power was above 15 W, where the surface quality deteriorated.[4]

Powder properties were examined to identify their effect on surface roughness. The surface quality depended on the bulk powder's density and surface quality. As packing density of the powder decreased, the surface roughness of the sintered part increased.[8]

Future Directions

Additive manufacturing with SLS is continually growing and being researched. Four topics which can group the bulk of current R&D literature are: 1) new SLS materials, 2) additives, 3) blends, and 4) new techniques. All new endeavors benefit the SLS field of study because they either improve a powder's process ability, improve mechanical properties, or add new specialty properties to a part. These new directions for SLS are potentially desirable for future investigations.

A variety of materials for SLS processing have been discovered including: polypropylene, high-impact polystyrene, polycarbonate, polyethylene (HDPE and UHMWPE), acrylonitrile butadiene styrene, and thermoplastic polyurethanes.[11-19] These either expand the availability of materials for SLS or have found use in medical applications. Various additives used with polyamides are clay, nanographene, carbon nanotubes and fibers, and potassium-titanium whiskers.[20-24] The additives either improve part mechanical properties or add new, specialty properties. Blends also achieve these same improvements, and success has been found with blending various polyamides, and polyamides with HDPE.[25,26] Finally, new techniques like surface finishing and incorporating pressure during SLS builds could prove useful to enhance part appearance or mechanical properties, respectively.[27,28]

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