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Full Length Article

Impact of chemical finishing on laser-sintered nylon 12 materials

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ABSTRACT

Additive Manufacturing offers many potential benefits including reduced tooling costs and increased geometric freedom. However, the surface quality of the parts is typically below that of conventionally-processed materials. This paper evaluates a new chemical post-processing method to reduce the roughness of laser-sintered Nylon 12 components. This process is called the PUSh™ process. The treatment reduced the surface roughness of sample parts from 18 μm to 5 μm Ra and largely eliminated roughness with length scales below 500 μm. Treatment did not affect the flexural modulus, flexural strength, or dimensions of 3.2 mm thick bending specimens, but it did significantly impact the mechanical properties of thin tensile specimens that are one to eight layers thick. The post processing reduced the breaking force of the samples, but it increased the ultimate tensile strength and elongation at break. The impact was largest on the thinnest parts. Significant sample shrinkage (12–20%) and weight gain (3.7–7%) from treatment was also observed in the tensile specimens. The results show that the PUSh™ process dramatically increases surface smoothness and elongation at break in thin specimens. It decreases the surface strength, but effects are negligible in larger samples.

1. Introduction

Additive manufacturing (AM) is a group of processes that produce parts by adding material under computer control from a digital definition of the desired geometry. Generally these processes create the desired geometry by depositing, curing, sintering, or binding the part a layer at a time. AM processes can form ceramics, metals, polymers, electronics, and biomaterials [1–11]. Example processes include binder jetting [12], laser sintering [4], laser melting [13], stereolithography [14], and fused deposition modeling™ [15].

The unique processing conditions in AM produce different mechanical properties and surface finish than traditional manufacturing processes such as injection molding, casting, and thermoforming. Whereas the surface finish of these traditional processes is largely determined by the mold, the surface of the AM components shows evidence of the layer-by-layer process. The roughness can be caused by the primitive features (lines and layers) of the AM process and can be influenced by process parameters like line spacing and layer thickness as well as part orientation [16–18]. The surface materials can also experience different processing conditions than interior regions. This often results in a lower density on the surface, a dull appearance, and a rough tactile feel to the surface. While these features may be helpful in some applications (improved friction), these characteristics are typically seen as undesirable artifacts of the AM processes. In as much as these surface characteristics are related to porosity and partially fused powder, they may also reduce the mechanical performance of the surface or the entire part. These effects are likely to depend n the material and the manufacturing process. Van Hooreweder, et al. [19] did not observe a significant difference in fatigue properties between injection molded and laser sintered Nylon 12 components, but the surface conditions may become more important with bending loads and/or small feature sizes.

AM components commonly undergo post-processing after printing. Many process types require removal of support material [20]. Some AM processes/materials utilize thermal post processing treatments (sintering, stress relieving) and infiltration to enhance the bulk properties of the component [21,22]. However, in commercial practice many components are also heated, sanded and/or coated to improve the surface feel and appearance [20,23]. These post-processing steps can add significant cost and hands-on labor to the manufacturing process [24]—potentially eroding the benefits of AM processing in some applications. These processes can also increase dimensional variation in the final part geometry [25].

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In laser sintering, several researchers have evaluated the relationship between the processing parameters and the surface roughness [26–29]. Typically, they see that there is a relationship between laser power and scan speed that minimizes the surface roughness. The minimum Ra value often falls around 20–30 μm [26,27]. Much of this roughness is related to contact of the sintered surface with adjacent powder. When no powder is spread over the sintered surface, the roughness decreases to as low as 1 μm [27]. However, not spreading powder over surfaces is not a general solution to improving surface roughness.

Nylon 12 is the most common polymer used in laser sintering and can also be produced using fused deposition modeling (FDM) [30]. However, this material is not treatable by chemical treatment methods applied to PLA and ABS. A new technique for chemical surface enhancement is available under license from the University of Sheffield that can produce a smooth and even shiny surface on Nylon 12 laser sintered components. This chemical treatment is identified as the PUSh™ process.

This paper will report on the impact of the PUSh™ post-processing methods on the surface roughness and mechanical properties of small Nylon 12 components in both tension and bending. Information is also provided on the dimensional and weight changes that occur during processing.

2. Methods

All laser sintered components were produced using an EOS Formiga P100. The bed temperature was 170 °C with 0.10 mm layers, 0.25 mm scan spacing. The laser power was 21 W for hatching and 16 W for the edges with a scan speed of 2500 mm/s hatching and 1500 mm/s on the edges. The material for all builds was PA 2200 with 50% virgin and 50% recycled powder. All specimens were printed in the YXZ orientation based on ASTM F2921-11 (part thickness aligned to the machine z-axis). All parts were positioned at least 45 mm from the sides of the build volume and at least 18 mm from the top and bottom of the build. After fabrication, the powder bed heating was turned off and the samples were allowed to cool for at least twelve hours before extraction. After removal, the parts were stored at laboratory ambient conditions (approximately 23 °C, 50% Humidity) for at least one week before testing.

ASTM D638-10 tensile tests were produced using Type I specimens with one, two, four, and eight layers. Ten parts were tested for each thickness. All parts were extracted from the powder bed and cleaned with compressed air. To avoid damage to the thinner parts, bead blasting was not used on any of the tensile specimens. The cleaned samples were randomly assigned to two groups. One group of five samples was post-processed with the PUSh™ process while the others were tested in the as-cleaned condition. The PUSh process affected all exposed surfaces of all parts. No spatial variation in the resulting surface properties was detected. The specimens were then tensile tested with a Tinius Olsen Model H5K-S UTM 5 kN testing system using a 500L laser non-contact extensometer to measure the strain. Directly before tensile testing, the weight and thickness of each sample was recorded. Weight measurements were done on a microbalance with 0.1 mg resolution. Dimensional measurements were done with digital calipers with 0.01 mm resolution.

Six bending specimens (design dimensions: $127 \times 12.7 \times 3.2\,mm^3$) were also produced using the same powder and processing parameters. Bending specimens were cleaned with compressed air and bead blasting. After cleaning, the specimen dimensions were measured with calipers and found to be $127 \times 12.8 \times 3.4\,mm^3$—closely matching the design dimensions. The ranges of the thickness and width measurements for each sample group was less than 0.05 mm. Three bending bars were post-processed with the PUSh™ process. Before bend testing, surface profiles were measured on treated and untreated specimens using a Dektak d150 with a 5 mm scan and a 5 μm tip. One scan was made on the top and one on the bottom of each test sample to get 6 scans each of both treated and untreated samples. Bending testing was completed using a 25 kN MTS 858 universal testing system according to ASTM D790-10 procedure B test method. The measured dimensions were used in calculating the flexural strength.

After testing, SEM imaging was done on a representative treated and untreated sample of the two layer tensile, eight layer tensile, and bending samples. The tensile specimens were examined near the fracture surface while the outside surface of the bending samples was examined. The SEM images were taken from the center regions of the bending bar specimens on the tensile stress side where the test fixtures did not contact the specimen. Subsequently, one treated and untreated bending bar was cooled in liquid nitrogen. A piece was then fractured off the end and the cross section imaged in the SEM.

3. Results and discussion

3.1. Surface and dimensional impact

During PUSh™ processing, the single layer samples curled significantly. The direction of curling varied between samples. Since all the parts were oriented the same way during printing, the curling seemed to be related to the PUSh™ processing conditions rather than residual stresses in the printed components. The post processing can clearly cause warping of very fine features. However, such uniformly thin parts are rarely used in laser sintering and all other parts remained flat and did not show any visible curling or warping from the process.

The PUSh™ treatment process produced a visible improvement in the surface smoothness that is clearly seen in SEM images of the surfaces before and after treatment (Fig. 1). The “before” images of the tensile specimens show loosely attached powder. In contrast, the bending specimens that were bead blasted do not show clearly identifiable powder particles on the surface. These images suggest that the bead blasting removed the loosely adhered surface powder from the bending specimens. SEM images of both sample types (bending and tensile) show a substantially smoother surface on the treated samples. This observation is reinforced by a much smoother edge for the treated component in the brittle fracture surfaces of the cooled bending bars as seen in Fig. 2. The high magnification images of the fracture surface show that the outer surface of the untreated part has a different structure than the bulk while the surface region of the treated samples shows no significant differences from the interior. The surface affected zone would likely be larger in the tensile specimens because of the thicker layer of loosely adhered powder due to the difference in part treatment methods: In Fig. 2, the imaged cross section also has fewer pores in the treated sample, but overall, the pores levels were similar in treated and untreated fracture surfaces.

The surface profilometry results on the bending specimens also show a clear benefit from the PUSh™ processing as seen in Fig. 3. The average and standard deviation in RMS roughness (R_q) values was dramatically reduced with treatment from an average and standard deviation of 21.8 ± 6.8 μm to 6.1 ± 1.7 μm. The arithmetic roughness values were similarly reduced from 18.0 ± 6.5 μm for untreated samples to 5.0 ± 1.6 μm for the treated. The untreated roughness values are consistent with literature reports for laser-sintered parts [26–28]. The power spectral density of the surface scans was calculated for all the profilometry scans to show the length scales of the roughness features before and after treatment [31,32]. As seen in Fig. 3, the PUSh™ treatment almost completely