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Mechanical Behavior of ABS after Interlayer Ultrasonic Peening Printed by Fused Filament Fabrication

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Abstract

Hybrid additive manufacturing brought new opportunities to improve the mechanical properties of materials by secondary processing of individual layers during printing. Previous work demonstrated interlayer shot peening during printing by fused filament fabrication (FFF) affected mechanical behavior while inadvertently imparting debris contamination from pulverized beads. The encouraging results motivated a study on the use of contamination free ultrasonic peening (UP) as an alternative interlayer surface treatment. Ultrasonic peening of FFF printed Acrylonitrile Butadiene Styrene (ABS) was studied in order to compare the effects on mechanical properties between ultrasonic peening and previously studied shot peening, different print orientations, and different interlayer peening frequencies. Two different layer peening frequencies (L4 and L8) were compared to an as-printed control (L0). Two orientations for each layer peening frequency were chosen for comparison. Tensile tests were conducted in order to observe the influence of interlayer UP on tensile strength of ABS parts.

Keywords: hybrid additive manufacturing, fused filament fabrication, polymer, ultrasonic peening

1. Introduction

Three-dimensional (3D) printing for polymer applications opens opportunities in the affordable manufacturing of devices. Recently, Hybrid Additive Manufacturing (Hybrid AM) has been used on metal parts in order to improve the mechanicals properties of 3D printed metals [12]. However, Hybrid AM is still not fully developed for 3D printed polymers, and research about Hybrid AM applied to polymers is still in development in order to apply the same interlayer treatments applied to metals [13].

The growing research on hybrid AM to enhance the mechanical properties of 3D printed parts is motivated by the need for lightweight and cost-effective components [1]. AM allows for complex part design, a range of various materials, lower cost, and a reduction in weight due to topology optimization [2, 3]. Hybrid AM combines layer by layer material deposition with interlayer surface treatments usually reserved for outer surfaces. Comparisons were performed on the effects on mechanical properties caused by Shot Peening (SP) and Ultrasonic Peening (UP) when applied to metal as a surface treatment [4]. The results showed that UP introduces deeper residual stress in printed parts, has a lower impact velocity, and a low roughness of the

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surface. It has been hypothesized that similar surface treatments on polymers may affect the mechanical properties of printed polymers.

Previous work has been conducted in order to observe the effects of SP on the mechanical properties of ABS parts printed with fused filament fabrication (FFF) [5, 6]. SP involves impacts of 0.4 to 0.6 mm balls at a high speed against the surface of a material to impart compressive residual stress. The results showed that surface shot peening affected the mechanical properties of the ABS by increasing the tensile strength when paired with certain print parameter changes but decreasing it with others. These varied results could have come from contamination of the sample or other damage due to the SP process. Metal particles were left behind and embedded into the sample, which could cause variance in the tensile tests. Furthermore, SP caused delamination to occur within the printed parts. Layers were peeling up and separating from the build plate due to the shock from the impact. The SP processes battered the samples and potentially caused more damage than residual stress. However, some of the samples showed improvement in the mechanical properties. Most notably, an increase in elongation during tensile tests was observed, which showed that SP increased the amount of strain an ABS printed part could handle before breaking (**Fig. 1**).

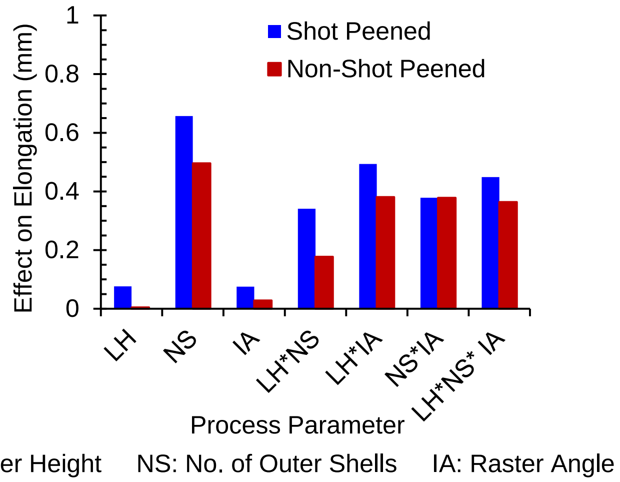

Fig. 1. Comparison of ABS samples shot peened and non-shot peened [6].

The advantage of UP compared to SP is the possibility to have interlayer peening without contaminating or damaging the samples. It involves dragging three pins across a surface while applying a strong vibration force to the sample as seen in **Fig. 2**. The force of vibration can be modulated by changing the amperage applied to the machine. This imposes residual stresses in a part similar to SP, but without leaving behind residue and battering the part [10,11].

UP was applied to ABS FFF printed samples and tensile tests were performed, to observe the effects of interlayer peening on the mechanical properties. Orientation of printing and interlayer peening frequency were selected as variables and ultimate tensile strength (UTS), fracture strength, elongation and Young's modulus were obtained from the tensile tests. The purpose of this research was to investigate the effects of interlayer UP on ABS printed parts. The results of UP were compared with SP to determine whether it improves the mechanical properties of the parts without the contamination and delamination that SP caused. In addition, an optimal peening frequency between two choices and an optimal printing orientation were determined.

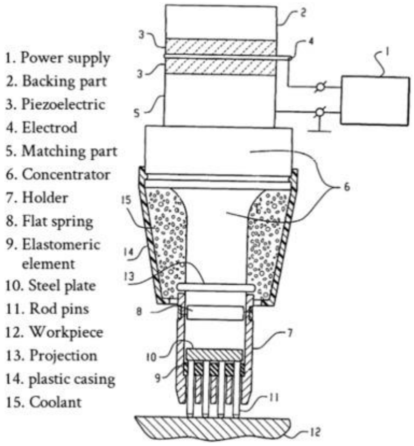

Fig. 2 Components of ultrasonic peening machine head [7].

Fig. 3 Stratasys Dimension FFF Elite printer.

2. Experimental Procedure

2.1 Fused Filament Fabrication (FFF)

ABS samples were printed by FFF on a Stratasys Dimension Elite printer (**Fig. 3**) using red and black colored filaments with a 1.75 mm diameter (**Table 1**). According to Stratasys [8], ABS*plus* colored materials have similar properties that can vary up to 10%. It was assumed for this research that black and red filaments, under identical printing conditions, had the same mechanicals properties. The sample dimensions were selected in accordance with ASTM 638D Type IV standard as shown in **Fig. 4**. Type IV was chosen so comparison was possible with previous research [6]. Layer thickness, raster angle, and infill density were kept constant (**Table 2**), while layer peening frequencies and orientations were changed. Printer calibration was performed to adjust the distance between the bed and nozzle. The temperature inside the build chamber was maintained at 70°C to facilitate adhesion of the support material to the build plate and part. The Stratasys ABS-P430 filament was extruded at 220°C, which was above the glass transition temperature of ABS, through the nozzle and deposited onto the support material.

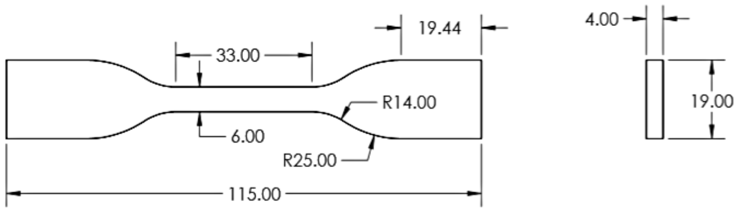

Fig. 4 ASTM 638D Type IV sample size in millimeters.

Table 1. ABS Grade P430 Properties from Stratasys [8]

ABS Characteristics	
Density	1040 kg·m^{-3}
Glass Transition Temperature	108 °C
Tensile Strength	33 MPa
Tensile Modulus	2.2 GPa

Table 2. Fused Filament Fabrication (FFF) Process Parameters

Variable	Constant
Layer Height	0.254 mm
Raster angle	-45°/+45°
Infill density	High
Build Plate Temperature	70°C
Nozzle Temperature	220°C

Two orientations of printing were selected: (1) flat orientation and (2) on-edge orientation, O1 and O2, respectively (**Fig. 5**). Three samples were printed for each different interlayer peening frequency for each orientation. The different frequencies were the control (L0), every four layers (L4), and every eight layers (L8). A total of 18 samples were printed with 9 for each orientation.

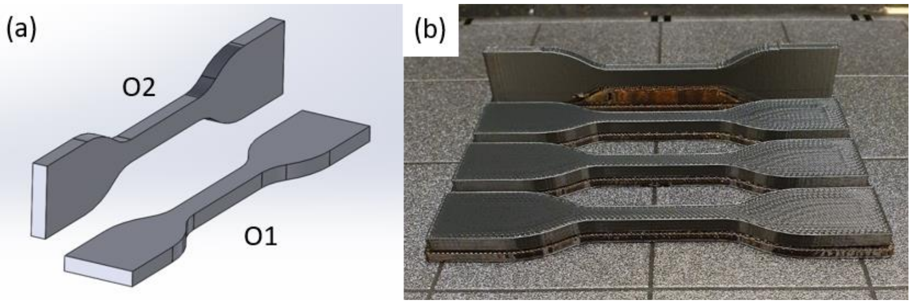

Fig. 5 a) Printing orientations and b) ASTM 638D Type IV samples from FFF printed in two orientations: flat (O1) for the first three samples and on-edge (O2) for the last sample.

2.2 Ultrasonic Peening

Hybrid additive manufacturing was performed by alternating FFF and ultrasonic peening (UP). The UP frequency was 20 kHz at 55% current amplitude. The percentage of current amplitude was selected according to a test sample, which was peened at 50%, 55%, and 70% (**Fig. 6**). The highest reliable peening condition that did not damage the sample’s surface was 55%. The ultrasonic peening was done under a continuous airflow and at room temperature (22°C). The FFF printed samples were removed from the 3D printer (according to the UP layer frequencies) by stopping the machine when the last layer was fully printed. The print plate was manually removed from the build chamber and the dog bone was maintained on its support material before being peened. Then, the print plate was returned to the printer and locked with fixed mechanical fasteners to continue printing in the original position. The thermal cycling from removing the sample from the printer and then putting it back inside was found to not have a significant effect on the sample, because the sample temperature inside the machine never rose above the glass transition temperature of ABS after the initial printing. Previous research on interlayer shot peened ABS found the glass transition temperature of the samples between 115°C and 135°C [5,6]. This led Hadidi *et al.* to conclude that the difference in thermal cycles upon printing and peening did not disrupt the layer bonding [5]. Also, specific attention was provided during this process, in order to let the ABS sample cool down before peening and preheat when the print plate was repositioned inside the build chamber. Each orientation had three control samples with no interlayer peening (L0), three samples with peening every four layers (L4), and three samples with peening every eight layers (L8) (**Fig. 7**). These peening frequencies were chosen to reduce damage to the support material and the part, to be frequent enough to cause a measurable affect to the part, and to be divisible with the total number of printed layers (X for O1 and Y for O2). A preliminary study showed that ultrasonic peening more frequently than every three layers damaged the support material. The control samples were printed all at once without being removed from the printer corresponding to L4 or L8 cycles. Previously mentioned research [5] suggests that this had no effect on the mechanical properties for comparison.

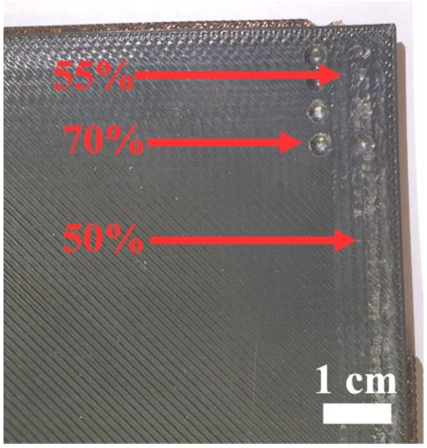

Fig. 6 Test sample peened at 50%, 55%, and 70% of its current amplitude.

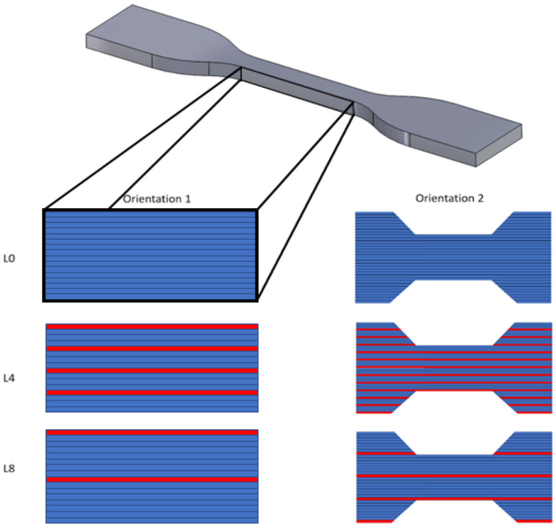

Fig. 7 Orientation 1 and 2 samples with each interlayer peening frequency selected.

The ultrasonic peening process tended to bend the samples, which caused the edge of the samples to peel off and sometimes the entire sample to come off the support. In order to minimize the sample damage due to the peening, double sided tape was placed between the sample and the support material. The poor effectiveness of the tape led to the use of a super glue and the application of a constant pressure on the sample edges during the peening.

2.3 Tensile Tests

In order to analyze the effect of UP on ABS FFF printed samples, displacement controlled tensile tests were performed on an MTS 810 tensile test machine at room temperature (22°C) with a 25 kN capacity load-cell and a displacement rate of 0.1 mm/min in accordance with previous work [6] and ASTM638. The extremities of the samples were securely held in the upper and lower grips. The samples were tested until they fractured, which took an average of 30 minutes for each sample. Each category of sample was tested three times, except for the L0-O2 (orientation 2), where only two samples were tested. The third sample broke while it was being loaded into the tensile tester. In total, seventeen samples were tested and analyzed. Engineering stress and engineering strain were calculated to obtain the ultimate tensile strength (UTS), the fracture strength, the Young's modulus (E), and the percent elongation. In order to obtain an accurate calculation of the Young's modulus, the slope of the elastic deformation needs to take into account the curve before and after the first plateau. The decision was made to remove the first plateau, which was due to the minor movement of the sample inside the grips and not to the deformation of the sample. The modified stress-strain curve is shown in **Fig. 8**, and the same method was applied to each stress-strain curve. Young's modulus was calculated using the slope of the modified curve. **Fig. 8** also shows the UTS, fracture strength, and elongation measurements.

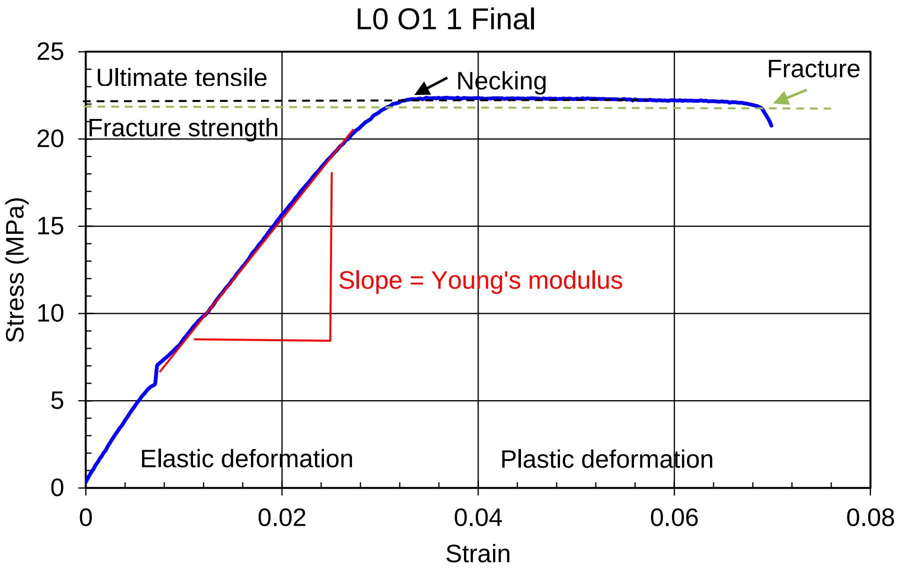

Fig. 8 Representative stress-strain curve of L0 samples printed in orientation one without the first plateau. The Young's modulus, UTS, elongation, and fracture strength are labeled.

3. Results and Discussions

3.1 Challenges with Ultrasonic Peening

Ultrasonic peening was performed, instead of shot peening, as a process for Hybrid AM of ABS samples in order to avoid metal fragment contamination. While UP seems to have no metal/glass contamination (**Fig. 9**), it also comes with its own set of problems, such as the samples warping during the peening process due to excess mechanical deformation. The challenges with ultrasonic peening below may have contributed to the variation in mechanical properties discussed below.

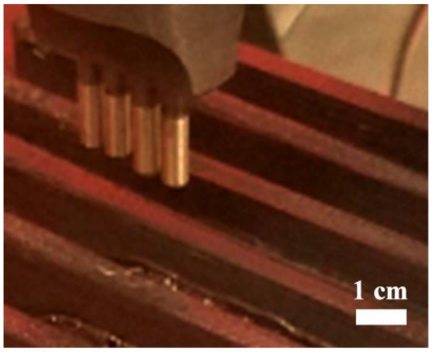

Fig. 9 UP of orientation 2 samples.

UP produces intense vibrations throughout the sample. The print plate was supported with plywood and clamped to the peening platform to reduce the impact of vibrations. However, the samples would sometimes be vibrated intensely enough to peel off the build plate or its support material as seen in **Fig. 10a**. After a part was unintentionally removed, a few methods to reattach the part to the print plate were attempted: double sided scotch tape and super glue. Neither of these methods worked as expected, and the parts continued to be vibrated off. When the part was successfully reattached to the build plate, the exact initial position of the part as difficult to reach. The result was a seam in the part as seen in **Fig. 10b**.

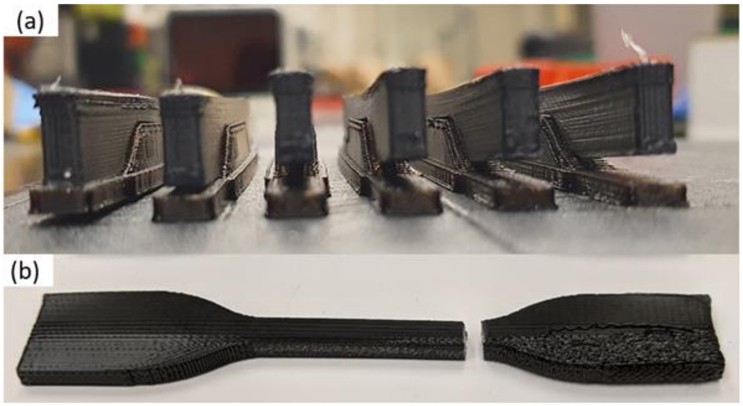

Fig. 10 a) Samples peeled from the build plate and from their support material after UP, b) Printed and fractured (after tensile test) sample that had a seam in the middle, because it was aligned improperly on the build plate after falling off.

3.2 Ultimate Tensile Strength

Interlayer UP frequency and orientation of layer deposition were found to impact the ultimate tensile strength (UTS). As the layer peening frequency and the print orientation changed, resulting UTS changed as well. **Fig. 11** compares the UTS for each layer peening frequency and both orientations. Concerning the orientation 1 (O1, in blue) and orientation 2 (O2, in red), UTS were 22.2 MPa and 27.4 MPa, respectively. These results are lower than the theoretical value given by Stratasys (33 MPa). This difference can be explained by the ASTM testing standards we used for our dog bones and tensile test parameters. Also, printing parameters, printing orientations, and analysis method based on a load-displacement curve that incorporated the testing devices' stiffness can explain the difference observed with Stratasys value. The impact of orientation is also noticeable with a relative difference between both orientations of 18.9%.

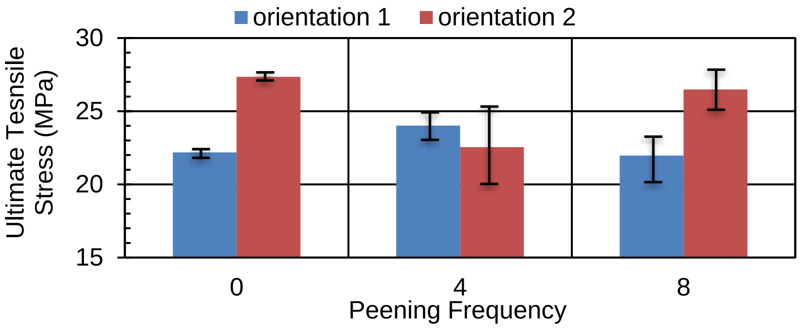

Fig. 11 Average ultimate tensile strength for each orientation and layer peening frequency.

As seen in **Fig. 11**, the UTS for orientation 1 were 22.2 MPa, 24 MPa and 22 MPa, for L0, L4 and L8, respectively. L0 and L8 have relatively similar UTS, which suggests that peening at every eight layers does not have a significant effect on the mechanical properties of ABS, whereas peening at every four layers increases the UTS. Concerning the second orientation, UTS were 27.4 MPa, 22.5 MPa and 26.5 MPa, for L0, L4 and L8, respectively (**Fig. 11**). As observed before, L0 and L8 UTS are similar, which led to the conclusion that peening at every eight layers is not sufficient. Peening at every four layers (L4) with the second orientation decreased the UTS. The results suggest more frequent ultrasonic peening is detrimental to the UTS.

3.3 Fracture Strength

As seen before, layer peening frequency and orientations have an impact on the mechanical properties of printed ABS by affecting its ultimate tensile strength. Then, a second analysis of the stress-strain curves was performed to obtain and compare the fracture strength of each sample. Fracture strengths of orientation 1 for L0, L4, and L8 samples were 20.6 MPa, 22.7 MPa, and 19.9 MPa, respectively (**Fig. 12**). Therefore, the fracture strength shows the same trends as observed in UTS: a higher value for L4 and similar results for L0 and L8. For orientation 2, the fracture strengths were 25 MPa, 21.6 MPa and 25.5 MPa, for L0, L4 and L8, respectively. Similar conclusion as UTS results can be made: L0 and L8 values are quite similar, whereas peening every four layers decreases the fracture strength.

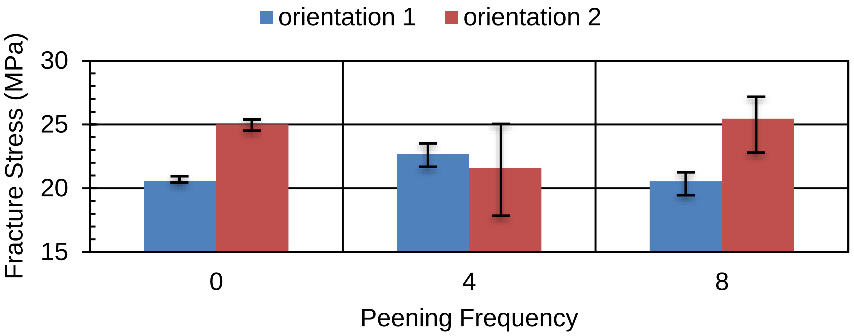

Fig. 12 Average fracture strength of each orientation and layer peening frequency.

A similar trend between the ultimate tensile strength and fracture strength was clearly observable. In both, values for L0 and L8 were highly similar, which suggest a lower limit on effective peening frequency exists. Also, it has been seen that the values of UTS and fracture strength increase for samples printed in orientation 1, whereas for orientation 2 these values decrease, compared to control samples.

3.4 Young's Modulus

According to Stratasys, ABS P430 Young's modulus is 2.2 GPa. This value can be compared to the control samples in both directions. Young's modulus in orientation 1 (O1) and orientation 2 (O2) were 0.78 GPa and 0.79 GPa, respectively. These values were substantially lower than expected from Stratasys data. The difference may be due to the thermal program applied to the ABS filament (printed at 220°C) and the printing method, which affect its mechanical properties. Also, Young's modulus is not affected by the orientation, with a relative difference between control samples in both orientations at 1.4%. Young's modulus for orientation 1 with L0, L4, and L8 were 0.8 GPa, 0.8 GPa, and 0.7 GPa, respectively (**Fig. 13**). The L4 and L8 samples had a lower Young's modulus when compared to L0. Considering orientation 2, the results obtained were 0.8 GPa, 0.7 GPa, and 0.7 GPa for L0, L4, and L8, respectively (**Fig. 13**). The Young's modulus decreases when the interlayer peening frequency decreases (*i.e.*, less frequent peening). The orientation and interlayer UP frequency seem to have slight effects on the Young's modulus, which do not correspond to the same trends seen in the UTS and fracture strength.

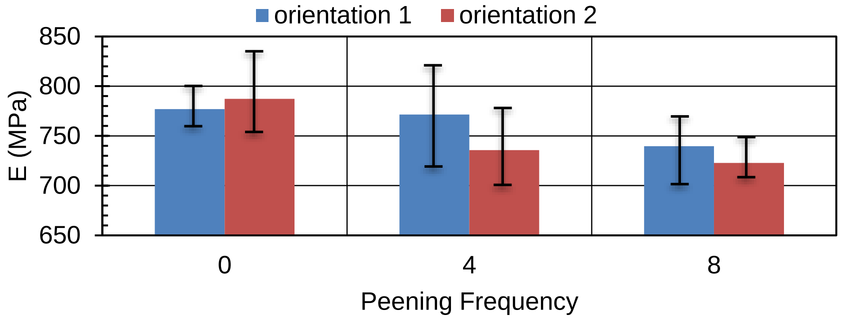

Fig. 13 Young's modulus as a function of the orientation and the layer peening frequency of ABS.

3.5 Elongation

According to literature [8,9], the elongation at fracture of ABS printed by FFF varies from 6% to 9%. The elongation at fracture of the control samples were 6.88% for orientation 1 and 8.35 % for orientation 2, which are within the range found in literature. The elongation at fracture was obtained for each orientation and interlayer peening frequency. Considering orientation 1, elongations for L0, L4, and L8 were 6.9%, 5.1%, and 6.3%, respectively. For orientation 2, elongations were 8.4%, 5%, and 5.6% (**Fig. 14**). In both orientations, L4 samples showed a lower elongation at fracture when compared to their respective control samples. In orientation 1, the elongation was almost the same for L0 and L8, which shows that ultrasonic peening has minimal impact on the L8 samples. However, a different observation is made for the second orientation. The interlayer UP has more impact on the elongation for orientation 2 than for orientation 1.

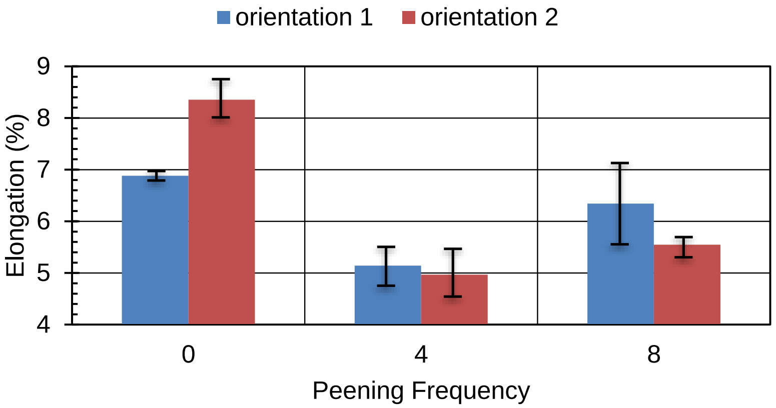

Fig. 14 Elongation in percentage of ABS FFF printed as function of the orientation and the layer peening frequency.

3.6 ANOVA

ANOVA tests were conducted with 95% confidence for ultimate tensile strength, fracture strength, Young's modulus, and elongation. Results comparing peening frequency in each orientation are presented in **Table 3**, and results comparing orientation with each layer peening frequency are presented in **Table 4**. The ANOVA method was used to identify significant parameters. When the P-value was lower than 0.05, the results were considered significant. As shown on **Table 3**, the difference in elongation between peening frequency is significant only in orientation 2, and the difference in fracture strength between peening frequency is significant for orientation 1. Differences in Young's modulus and UTS between peening frequencies were not significant.

Table 3. ANOVA between Peening Frequency with 95% confidence for both Orientations

	Orientation 1		Orientation 2	
Variables	P-value	F-stat	P-value	F-stat
UTS	0.159	2.537	0.125	3.247
Fracture Strength	0.028	6.867	0.285	1.632
Young's Modulus	0.499	0.783	0.295	1.574
Elongation	0.051	5.09	0.004	30.356

Table 4. ANOVA between Orientation with 95% confidence for each Interlayer Peening Frequency

	L0		L4		L8	
Variables	P-value	F-stat	P-value	F-stat	P-value	F-stat
UTS	0.001	903.49	0.513	0.513	0.028	11.436
Fracture Strength	0.003	74.55	0.643	0.250	0.030	10.831
Young's Modulus	0.805	0.072	0.414	0.828	0.507	0.530
Elongation	0.020	20.83	0.678	0.200	0.406	0.929

According to **Table 4**, the UTS and fracture strength have significant differences between orientation for L0 and L8. The elongation was significantly different between orientations in L0 only, and the Young's modulus was not significantly different between orientations.

ANOVA test showed that changing the UP frequency does not significantly affect the UTS, and orientation 2 had a significantly higher UTS in L8 and in control samples. Fracture strength for L4 peening frequency was significantly higher than the control and L8 for orientation 1, and the fracture strength of orientation 2 was higher than that of orientation 1 (only significant in control and L8 peening frequencies). The elongation of the control sample was significantly higher in orientation 2 than with UP, and orientation 2 had a significantly larger elongation than orientation 1 (only significant for the control peening frequency). Finally, the Young's modulus was not significantly different between any procedure.

To discuss the previous results, it is important to keep in mind that the printing and ultrasonic peening process had issues, due to warping of the samples, which may have interfered with these results. The differences observed between control samples (L0) and data from Stratasys could be explained by the parameters used to print the ABS samples, the testing methods and theirs parameters, and the thermal cycles applied to the part. This information on the testing procedure used by Stratasys was not readily available, which leads to a lack of explanation concerning our results for control samples in comparison with manufacturers specifications. However, it is still possible to analyze our results and the impact of orientation and interlayer peening frequency.

Tensile tests performed on ABS samples highlighted the difference between the printing orientations. Indeed, orientation 1 (O1) showed lower UTS, fracture strength, elongation, and Young's modulus when compared to orientation 2 (O2) for the control samples. However, O1 had higher UTS, fracture strength, and Young's modulus for the L4 samples. This conclusion can be explained by the innate difficulties of ultrasonic peening in orientation 2. As mentioned before, orientation 2 is less common, due to the difficulty to print and process a thin sample. Sample warping in orientation 2 was more common than in orientation 1, which may lead to a reduced adhesion between each layer and a corresponding decrease of mechanical properties.

As previously mentioned, L8 seemed to have the same mechanical behavior as L0, which leads to the conclusion that L8 is not sufficiently affecting mechanical properties. L8 layer peening frequency was too low to have a cumulative and enabling impact on the mechanical properties of the ABS samples. The thickness of 8 layers is too infrequent to induce a residual stress. A slight decrease of Young's modulus for L8 samples was observed, which may not be related to the UP, but it might be related to the effect of the thermal cycling used with FFF (printed temperature of 220°C).

Finally, ultrasonic peening at every 4 layers (L4) seems to have the highest impact on the mechanical properties of the ABS samples. Indeed, as a function of the orientation, L4 had a higher value concerning UTS and fracture strength, and it had a lower value for elongation for O1. Concerning O2, UTS, fracture strength, and elongation were lower for L4 than for L0 and L8. Then, the Young's modulus in O1 was less affected by UP with a slight decrease between L0 and L4 (0.7% in O1 and 6.5% in O2), whereas in orientation 2 the decrease was more important (4.9% in L4). Peening every 4 layers allowed highly impacted the mechanical properties of ABS.

4. Summary and Conclusions

Ultrasonic peening was used on FFF printed ABS samples in two orientations and peened with different layer peening frequencies. Tensile tests were performed on each sample to determine the effect of ultrasonic peening on the mechanical properties of ABS. Previous work with shot peening as surface treatment contaminated the surface of the ABS samples, which explains the choice to work with ultrasonic peening. UP is an aggressive mechanical process that does not egregiously contaminate the surface.

Two layers peening frequencies were selected: every 4 layers (L4), every 8 layers (L8), and control samples with no peening (L0) were analyzed. Tensile tests highlighted the impact of orientation on the ultimate tensile strength and fracture strength. In orientation 1, L4 had the highest values, whereas these values were the lowest in orientation 2. Also, the results did not show significant differences between L0 and L8, so peening at every 8 layers was shown to not be effective. Concerning the elongation, it was found that L4 had the lowest elongation during tensile tests. The Young's modulus was calculated and its value decreased when the layer peening frequency decreased from L4 to L8. ANOVA tests were performed over these results and outline the lack of significant parameters for Young's modulus. However, interlayer peening of the ABS samples affected the UTS, fracture strength, and elongation with statistical significance.

Future work will be focused on different peening layer frequencies such as peening every two or six layers. These results will be compared to the pattern observed for UTS and fracture strength as a function of the orientation. The major issue with ultrasonic peening was the warping of the samples. Consequently, future improvements are needed to be able to reduce the warping of the samples and reduce the risk of errors in repositioning the sample.

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