Effects of nozzle-bed distance on the surface quality and mechanical properties of fused filament fabrication parts

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Abstract. Fused filament fabrication (FFF) is a widely studied additive manufacturing technology. However, the effect of initial nozzle-bed distance (NBD) is neglected in most of the studies. In this paper, the effects of the NBD on FFF process were investigated. The optimal NBD for fabrication of high quality FFF parts were evaluated based on the surface quality and mechanical properties of Acrylonitrile Butadiene Styrene (ABS) parts. With the NBD increases from 0.083 to 0.20 mm, the roughness of surface increases first and then lowered down, with best surface quality observed at NBD of 0.10 mm, which induces an average altitude intercept of approximately 102.0 μm. More interestingly, the inter-layer adhesion decreases obviously with the NBD increasing. It was found that the NBD influences the voids formation in the first layer and hence the heat dissipation mechanism, which further influenced the interfacial bonding of the following layers. At higher NBD value, the heat dissipation mechanism also induces the decrease of part mechanical properties, such as tensile, compression and bending strength.

1. Introduction

Additive manufacturing (AM) technology has developed rapidly and received considerable attention of the processing industry [1]. Several AM techniques have been developed, such as selective laser sintering (SLS), laminated object manufacturing (LOM), stereo-lithography (SLA), and fused filament fabrication (FFF). Among all the techniques, FFF has been commonly used in conceptual models, prototypes, engineering components fabrication, due to its simplicity and cost-effectiveness [2]. The physical process of FFF is shown in Figure 1a. In the FFF process, the thermoplastic filament feedstock is propelled into the heating section of the nozzle via a pinch roller. The filament is then melted into semi-liquid in the heating block and extruded by the extruder mechanism through the extrusion nozzle. As the material is deposited onto the building platform, it cools, solidifies and bonds with the adjoining filaments. When one layer is completely deposited, the building platform moves down at a certain layer thickness, and the next layer will be deposited. The part is completely fabricated by repeating this process layer-by-layer [3].

The FFF process is controlled by many parameters, the parameters play an important role in ensuring surface quality and mechanical properties of the final part. Therefore, the selection of
appropriate parameters is the key to successful printing [4]. Many researches were focused on the optimization of the process parameters and explored the relationship between process parameters and the final product quality. Anitha et al. [5] studied the effects of process parameters including road width, thickness, and printing speed on the surface quality of ABS part. They found that the layer thickness is the main influencing factor of the surface quality, which become worse with layer thickness increases. Christiyan et al. [6] investigated the effect of layer thickness and printing speed on the tensile and flexural strength. It was found that low layer thickness and low printing speed can improve the tensile and flexural strength due to sufficient adhesion between layers. Sood et al. [7] studied the effect of part orientation, layer thickness, raster angle, part raster width and raster-to-raster gap on the quality of printing parts. It revealed that the decrease of layer thickness will promote the increase of strength, due to the thermal diffusion between adjacent filaments increasing. Spoerk et al. [8] studied the effect of layer thickness and layer designs on the intra- and inter-layer strengths of 3D-printed parts. They found that the defect concentration can be reduced with a printing temperatures of 250 °C and layer thicknesses of 0.25 mm, which improved the intra- and inter-layer cohesion of adjacent filaments and effectively improved the tensile strength.

![Figure 1. Illustration of (a) the FFF process and (b) the nozzle-bed distance parameter.](image)

The above studies indicate that the layer thickness is important on the surface finish and mechanical strength of FFF parts. However, these studies are all based on a default thickness of the nethermost first layer, i.e. the nozzle-bed distance (NBD), which is usually the thickness of a piece of paper suggested by the merchant of open-source 3D printer. As a result, there is no standard for the NBD value, since the typical thickness of a piece of paper is in the range of 0.07–0.13 mm. The NBD value has been suggested to be effective for the good adhesion of the manufactured part with the building platform. Ravi et al. [9] provided the only report on NBD on strut width (SW) by printing single-layer scaffolds aiming at control the printing accuracy. However, the influence of NBD on the surface quality and mechanical properties (tensile strength, bending strength and compression failure) were not reported. To clarify the effect of NBD, this paper aims to explore the impact of the MBD value on the surface quality and the mechanical properties of FFF manufactured ABS part. The optimal NBD was evaluated based on the surface quality and mechanical testing results.

2. Materials and methods

2.1. Material

The FFF samples are made of acrylonitrile butadiene styrene (ABS) thermoplastic resins. High impact ABS thermoplastic (Polylac® PA-747, ChiMei, Taiwan, China) with a density of 1.03 g/cm³ was used to make ABS filament. For this purpose, the received ABS pellets were vacuum dried at 80 °C for 12 h before processing. A single screw extruder (SHSJ35, Dongguan Plastic Machinery, China) with a 4 mm diameter die was applied to fabricate the filament. Based on pilot experimentations, the extrusion temperature was set at 175-190 °C, the extruder screw speed and traction speed were set at 10.5 rpm and 6.0 rpm, respectively. The diameter of obtained ABS filament was inspected in-situ by a laser
diameter measuring instrument (LST-25) with a precision of ± 0.002 mm. The diameter of fabricated filaments was measured to be 1.75 ± 0.035 mm by 20 point along 5m length.

2.2. Samples preparation
All 3D printed samples were manufactured by a commercial open-source FFF 3D printer (Huaway 3D-304, Shenzhen Huaway Technology Co, Ltd. China) with a printing accuracy of 0.01 mm. The printing surface is a glass covered with blue tape and the level of the building platform was adjusted by 4 screws at four corners. The initial nozzle-bed distance (NBD) was calibrated with standard copper sheets of 0.083 mm, 0.10 mm and 0.20 mm thickness, by placing them between the nozzle and the bed. Illustration of the NBD parameter was shown in Figure 1b. Samples for mechanical studies of FFF samples, including tensile, three-point bending and compression, were designed according to ISO 527, ISO 14125 and ISO 604 standard, respectively. The Cura 2.5 software was used to slice the CAD model and prepared the G-Code for 3D printing. Because the first layer will not well cohered with the building platform at large NBD, the shrinkage can lead to a failure of printing. The maximum NBD without warping deformation was 0.20 mm in this study. Other printing parameters are as follows: printing speed was fixed at 30 mm/s; object infill 100%; layer thickness 0.20 mm; nozzle diameter 0.40 mm; the nozzle temperature and heat plate were set at 230 °C and 100 °C. For consistence, all samples were printed in the middle of the building platform with one sample at a time. The processing parameters of the FFF samples were summarized in Table 1.

Table 1. The printing parameters for ABS.

| Parameters                  | ABS   |
|-----------------------------|-------|
| Extruder/Bed temperature (°C) | 230/100 |
| Printing speed (mm/s)       | 30    |
| Infill density (%)          | 100   |
| Layer thickness (mm)        | 0.20  |
| Nozzle diameter (mm)        | 0.40  |
| NBD (mm)                    | 0.083, 0.10, 0.20 |

2.3. Characterization

2.3.1. Tensile Testing. Dimensions of samples are specified in ISO527. Tensile tests were performed on samples using a Universal Mechanical Testing Machine (Instron 5569A, USA) with a load cell of 30 kN. The constant tensile speed was set to be 5 mm/min. Five printing samples were made for each tensile test. The average values of tensile strength and modulus were presented.

2.3.2. Three-point bending tests. The three-point bending tests were performed according to the ISO 14125 Standard with the loading rate of 2 mm/min. Samples are held on two supports rollers (maintaining a support span of 64 mm) and a load is applied in the middle until deformation of the sample reached 25%.

2.3.3. Compression failure tests. In order to investigate the effect of NBD on the compression failure response of the 3D printed parts. The sample was prepared in one printing orientations (lying sample) in accordance with ISO 604 standards. The mechanical tests were carried out with a 30 kN load cell at a loading rate of 2 mm/min.

2.3.4. Inter-layer adhesion tests. The T-peel samples were printed with 10 layers that parallel to the print bed. The sample is tested using an Instron™ 5569A. A notch was printed at the interface of two
layers for crack formation to begin. Inter-layer adhesion tests were performed at an extension rate of 1 mm/min. Five samples in each group were tested.

2.3.5. *Scanning electron microscopy (SEM).* Morphological studies of FFF samples were done using a Field Emission Scanning Electron Microscope (QuantaTM 250FEG, FEI, USA). Cryo-fractured samples were prepared in liquid nitrogen to get a preferable surface. All sample surfaces were sprayed with gold before observations. SEM images were obtained at an accelerating voltage of 10 kV.

2.3.6. *Surface accuracy analysis.* Surface accuracy was measured by Laser Scanning Confocal Microscope (VK-X200K, KEYENCE). The surface quality in this study is expressed with the altitude intercept, which is widely used in the industrial field. To ensure the accuracy of the experiment, the top surface of the samples was analysed. For each test, five samples were prepared and tested, the obtained average altitude intercept value were presented in this report.

3. Results and discussion

3.1. 3D surface topography
To study the influence of NBD on the road bonding quality, the surface profile and topography of the samples are shown in Figure 2. From the typical 2D contour map shown in Figure 2a, we can see that the surface presents high waviness. As shown in Figure 2b, obvious ridges were formed between the raster filament, and the average altitude intercept is about 156.4 μm when printed with a NBD of 0.083 mm, leading to worse surface quality. Besides, the valleys between the filaments also appear. It noteworthy that, with increasing of the NBD, the average altitude intercept first decreased to 102.0 μm and then slightly increased to 111.1 μm for NBD of 0.10 mm and 0.20 mm, respectively. As shown by the 3D profile in Figure 2b-d, the NBD have showed profound effect on the raster bonding and surface finish, since an identical layer thickness is used for all the samples. The markedly flattened ridges on the sample surface of 0.10 mm NBD is thus due to the first layer. With large NBD value, the valleys between filaments is also observed, indicating less bonding between the filaments due to enough space for raster deposition.

![Figure 2](image)

*Figure 2.* (a) The surface profile of 3D printed samples. (b) (c) (d) 3D surface topography of the samples at NBD of 0.083 mm, 0.10 mm and 0.20 mm, respectively.
3.2. Morphology characterization

The spreading and bonding quality of printed ABS were characterized with cryo-fractured samples by SEM. As shown in Figure 3a and b, for all NBD used, triangular and voids presented in all samples. These voids are mainly the gaps between the filaments deposited during printing. When the NBD is 0.10 mm, the semi-molten filaments were closely deposited on the building platform, and there are no air gaps observed between the filaments in the first layer. The well-bonded first layer can reducing the heat loss from the second layer to the printing bed, which ensures the well-bonding of the filament in the following layers. As we can see from Figure 3a and b, the voids of 0.10 mm samples are smaller than that of 0.20 mm NBD samples. Whereas for 0.20 mm (NBD), the deposited elliptical shape filament produced obviously ridge and valley, and the bad-bonded first layer accelerated the heat transfer to the platform and environment [10]. As a result, the sintering area between filaments decreases and triangular-shaped voids or gaps between the beads were created in the next few layers. The formed void is large. Different NBD also induced different tensile fractured surfaces, as seen in Figure 3c and d. When the NBD is low (0.10 mm), these triangular pores are mostly aligned in the direction of loading, and they are assumed to have inconspicuous effect on the mechanical performance of the samples. However, when the NBD is higher (0.20 mm), it can be seen that not every layer of adjacent filaments bonds have the same size necks. Actually, several layers near the bottom of the sample build thin sintering necks. By comparing these results, around five layers are influenced at large NBD, which is assumed to be the local variations in temperature as well as differences in localized cooling rates [11] induced by NBD.

![Figure 3. SEM micrographs of 3D-printed samples printed from neat ABS; Cryo-fractured surfaces with NBD of (a) 0.10 mm and (b) 0.20 mm, tensile fractured surfaces with NBD of (c) 0.10 mm and (d) 0.20 mm.](image_url)
3.3. Quantifying inter-layer adhesion

The inter-layer adhesion between filaments was tested in order to qualify the effect of NBD on the strength of inter-layer adhesion produced by FFF. A 3D printed T-Peel model based on the ASTM standard [12] was used to study the inter-layer adhesion properties. The sample is tested using an Instron™ as shown in Figure 4. The layer tensile load as a function of extension is presented in Figure 5. The mean values and deviations are shown in Table 2.

![Figure 4. Schematic diagram of T-peel sample.](image1)

![Figure 5. Tensile load as a function of extension for ABS during the T-peel experiment.](image2)

The failure all propagated along the interface. As seen in Figure 5, the force of interfacial bonding for ABS decreased by 38.48% with NBD increased from 0.10 mm to 0.20 mm. This is a clear indication of a dramatic influence of NBD on the interfacial adhesion between layers. In the process of printing, the heat transfer mainly includes the heat conduction from filament to adjacent filament, the building platform and radiative heat loss to the environment. From Figure 3, we can see that the minimum void in the first layer weakened the heat conduction to the platform and thus increased the sintering time due to lower NBD. According to the well-known Frenkel–Eshel viscous sintering model, the larger the sintering time, the best bonding of inter-layer adhesion.

![Table 2. Summary of measured mechanical properties.](image3)

| NBD (mm) | Tensile tests (MPa) | Flexural tests (MPa) | Compression tests (MPa) | Inter-layer adhesion (N) |
|----------|---------------------|---------------------|------------------------|------------------------|
|          | strength            | modulus             | strength                | modulus                | strength            | modulus             |
| 0.10     | 35.53±1.51          | 2299.53±89.75       | 76.35±2.56              | 2302.63±68.37          | 63.18±1.73          | 1726.74±35.08       |
| 0.20     | 32.62±2.19          | 2091.12±106.28      | 70.19±1.68              | 2270.80±65.67          | 59.93±1.49          | 1653.08±34.39       |

3.4. The stress-strain of compression test

Figure 6 shows the stress-strain plots of compression test at different NBD, which show a clear fracture yield point. When the NBD changes from 0.10 mm to 0.20 mm, the compressive strength (shown in Table 2) decreases from 63.18 MPa to 59.93 MPa (decreased by 5.14%), indicating the slight influence of NBD on the compression strength. It can be seen from Figure 7 that the failure patterns of compression samples depends on the NBD. The outer layers of sample close to the side of the building platform have a brittle behavior, which were fractured first. When the NBD increases, inter-layer adhesion will then cracked, indicating the relative low adhesion performance of layers under high NBD.

3.5. The mechanical response of tensile and bend

Figure 8 and 9 show the stress-strain curves of tensile and bending test as indication of the NBD effect. With the increase of NBD, the tensile strength of ABS decreased by about 8.19%, while the elastic modulus decreased by 9.06%. The bending strength of the ABS also decreased by 8.07%, and the bending modulus of the amorphous ABS decreased only 1.38% since it was very small. The mean
values of mechanical strength are shown in Table 2. In general, as it clearly emerges from Figure 8 and 9 that the strength and elastic modulus are decreased with the NBD increase. As discussed in section 3.2, the reduction of tensile properties could be attributed to presence of some voids between the deposition filaments. During the printing process, each filament adheres to another to build a layer and quickly solidifying after being deposition. While with NBD increasing, the voids between filaments in the first layer become large, which lead to greater heat dissipation, resulting in high porosity and poor adhesive strength between the interlayers or across filaments [13].

Figure 6. Stress-strain plot of compression test samples of ABS.

Figure 7. The failure patterns of compression samples.

Figure 8. Stress-strain plot of tensile test samples of ABS.

Figure 9. Stress-strain plot of bending test samples of ABS.

4. Conclusions
In this study, we have successfully clarified the effects of the NBD on the surface quality and mechanical properties of ABS samples. The 3D surface profiles reveal that surface quality was good at a NBD of 0.10 mm, the average altitude intercept is about 102.0 μm. The SEM images demonstrate that the voids between filaments in the first layer become large with the NBD increasing, which further increased the following inter-layer adhesion. The enhanced heat dissipation at large NBD decreased the force of interfacial bonding from 163.58 N to 100.64 N by 38.48% when NBD increased form 0.10 mm to 0.20 mm. With the nozzle-bed distance increasing, the heat dissipation mechanism also induces the decrease of part mechanical properties, such as tensile, compress and bending strength or modulus due to the porosity increase. Taking the surface quality and mechanical strength into account, the optimized NBD is found to be 0.10 mm in our study. This research provide valuable insight into the inter-layer bonding process for researchers and 3D printing enthusiasts, helping them to make improved products.
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