An Evaluation of Components Manufactured from a Range of Materials, Fabricated Using PolyJet Technology

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With advances in additive manufacturing, particularly in the area of three dimensional (3D) printing, it is becoming possible to generate small quantities of functional components. As with all manufacturing technologies, the ability to reproducibly generate parts with defined dimensional accuracy and surface finish is of key importance. This work characterises the ability of one such technology, PolyJet 3D printing, to produce such parts. In order to characterise the output from the manufacturing technique, a test part was designed and manufactured in three alternative materials representative of alternative grades across a commercial range. The designed test part consisted of positive and negative feature types printed both in the direction of, and normal to, the print head traverse direction. The test parts were characterised in terms of dimensional accuracy in three dimensions and also in terms of surface finish. Differences in dimensional accuracy and surface profile were observed depending on the orientation of the feature relative to the print head travel direction.

Keywords: PolyJet; 3D printing; Additive manufacturing; Photopolymer; Inkjetting.

Introduction.

Additive manufacturing (AM) is an umbrella term encompassing a range of manufacturing techniques that build a given 3D part in layer by layer fashion [1]. Among these additive manufacturing techniques, 3D printing is perhaps the most ubiquitous. 3D printing techniques have traditionally been used for applications in rapid prototyping at the preliminary stage of the product design life cycle. In this context, mechanical characteristics such as load bearing ability, dimensional accuracy, and build speed are not critical to the overall part production. However, recently, and in parallel with improvements in 3D printing technologies, 3D printed parts are increasingly being used as functional components for applications in low-volume high-value industries such as aerospace, automotive, tooling, jewellery, dentistry, and audiology [2]. With the move toward higher volume functional components, the requirements of both processing technologies and material properties have become more stringent [3].

From a processing technologies perspective, among the main challenges are both surface finish and dimensional accuracy of manufactured components. Given that a unique feature of 3D printing is the promise of rapidly customisable parts [3], for example, for personalised medical implants, it is of critical importance that any chosen manufacturing technology has the resolution to achieve required tolerances on dimensional accuracy and surface finish.

Among the current commercially available processing technologies photopolymer based inkjet printers show significant promise in terms of build speed and resolution [4]. The principle of the PolyJet 3D printing technique is depicted in Figure1. Figure 1 (A) illustrates a print head traversing across the printer bed in the ‘x’ direction, as indicated in Figure. 1. The print head selectively jets a layer of photo-curable polymer (shown in yellow Figure 1 (A)) onto the print bed. This layer is then partially cured through irradiation with an ultraviolet light source (shown in Figure 1(B)). The print bed is then translated in the ‘z’ direction as indicated in Figure 1 and the process of deposition of another layer is repeated. Where hollow parts or overhangs are required, the print head deposits a layer of removable gel-like support material that does not crosslink with the main build material.

The principle of PolyJet printing borrows heavily from the ink jet printing industry, as such the enabling technology is already, to a large extent, well established. As a corollary of the capacity for inkjet printing to print multiple colours, PolyJet 3D printing is among the few methods of 3D printing capable of printing multiple materials in a single build. Using PolyJet technology, single parts can be produced with a combination of alternative materials including combinations of thermoset and elastomeric materials. Further, fully cured models can be handled and used immediately, without additional post-curing.

Parts created using 3D technologies are, by the nature of the process, anisotropic [5–9]. Based on this anisotropy, the orientation of a given part relative to the traversing nature of both the print head and the printer bed may affect the quality of the finished part or key features of a given part.

The effect of build direction/orientation in the PolyJet process has been studied previously in respect to tensile stress [8, 10–13], surface roughness [8, 14], hardness [13], viscoelasticity [15], and thermomechanical properties [16]. This paper investigates the effect of build orientation on dimensional accuracy and surface finish of a given part using a commercially available PolyJet based printer, the Objet 260 Connex1 from Stratasys. The Objet260 Connex1 is a compact, entry level edition of Objet's pioneering line of multi-material 3D printers. The printer has the capacity to print 14 alternative materials and up to 3 alternative materials in a single build. In terms of technical specifications in relation to build quality, there is no discernible difference between the Connex1 and other machines the Objet260 Connex range. As such the Objet 260 Connex 1 represents an ideal test bed for investigations into processing capabilities of PolyJet technologies.

Materials and Methods

Test Piece.

In order to assess the dimensional accuracy and quality of surface finish of the Objet 260 Connex 1, a test part was designed. This test part contained positive and negative features types; both in the direction of, and normal to, the print head traversing direction could be interrogated. The designed part is shown in Figure 2. A similar test piece incorporating positive and negative features was used by Shallan et al. [17] to assess the dimensional accuracy of their stereolithography (SL) 3D printer (MiiCraft, Taiwan). The test piece, shown in Figure 2, consists of a 30mm x 30mm x 2mm cuboid part containing pairs of features printed normal to, and in the direction of, the print head traversing direction. These features were designed to be 1mm x 10mm in the horizontal plane. Each feature pair consists of a feature protruding from the surface (positive feature) and a feature inset into the surface (negative feature) as indicated in Figure 2. The feature height and depths are +500µm and -500µm respectively. Also shown in Figure 2 is a 15mm x 10mm area where surface profile measurements can be carried out across multiple locations.

The test parts were generated in SolidWORKS 2014-2015 and saved in 'Stereolithographic' STL format for subsequent transfer to an Objet 260 Connex1 commercial 3D printer from Stratasys. STL files are generated by tessellating the surface of the specified part into a series of small triangles. The STL file format is the conventional file format used for 3D printing. On saving the part, custom STL parameters were used in an effort to enhance part quality. The 'deviation' parameter used to control whole part tessellation, influencing whole part accuracy, was changed from 0.02mm to 0.0025mm. The 'angle' parameter, influencing smaller detail tessellation was modified from 10deg to 0.5 deg. These modifications, representing the best available through SolidWORKS, had the net effect of significantly increasing the file size for the parts, typically on the order of a ten-fold increase. These modifications had a negligible effect on actual build times of the parts.

In total, three materials were tested [18,19]:

- Vero White RGD835 is among the more established PolyJet materials and is closely aligned to Acrylonitrile Butadiene Styrene (ABS) and High-Impact Polystyrene (HIPS) in terms of properties. Vero White RGD835 falls into the Stratasys ‘standard category’ of plastics.
- High Temp RGD 525 has a higher glass transition temperature (65 deg C) than other PolyJet materials. This can be further increased through post processing heat treatment. High Temp RGD 525 is a member of the Stratasys ‘engineering plastics’ family.
- Clear Bio-compatible MED610 is a relatively new PolyJet material and was evaluated for biocompatibility in accordance with standard DIN EN ISO 10993-1: 2009, Biological Evaluation of Medical Devices-Part 1: Evaluation and testing within a risk management process.

For each material, four parts were printed during a single production run. Post processing of the parts included a high pressure water wash using a Genie400 encapsulated washing and finishing system. This wash was followed by cleaning in a 1% ($^{w}/_{v}$) NaOH solution as per the manufacturer recommendations to remove any support material. The post processed parts were subsequently tested in terms of dimensional accuracy and roughness.

Dimensional Measurements.

Dimensional accuracy of the test parts was interrogated using a Keyence 3D Digital Microscope (VHX2000E). The VHX Series Digital Microscope which has in increased depth of field and longer working distances than traditional optical microscopes allowing for the generation of surface three dimensional profiles to an accuracy of up to +/- 1µm, depending on the magnification used. In terms of Keyence settings, the images were acquired using a x200 magnification giving a field of view, for a single image of 1620 x 1240µm. The sample was illuminated using a combination of direct and transmitted light. This combination of illumination had the net result of enhancing the contrast of the image, without impacting adversely on the integrity of the dimensional measurement.

In order to interrogate each feature pair, at multiple locations, an entire three dimensional profile of each feature pair was generated using a stitching function within the Keyence VHX2000E software. This stitching function allows a number of images taken from adjacent areas of a given part to be combined (stitched) together to generate a larger image, more representative of the overall area of interest. Sample images taken from the Keyence 3D microscope are shown in Figure 3(A). Once the image has been acquired line profiles are taken across the image to determine a two dimensional profile across the part (Figure 3(B)). Three line profiles were taken for each feature pair.

Roughness Measurements.

Roughness measurements were carried out using a WYKO NT1100 white light interferometer from Vecco and interrogated using Gwyddion data visualisation and analysis software. In a similar manner to dimension testing, averaged line profiles of roughness were taken normal to and along the direction of printing for comparison. Further, given the anisotropic nature of the part as a result of manufacturing process, the waviness of the part was measured normal to, and in the direction of, printing.

Acquired images were 736 x 480 pixels in dimension corresponding to a real world area of 2.444 x 1.859 mm. For each part three locations were interrogated. Preprocessing of the images consisted of utilising the leveling and zero fixing functions within Gwyddion. Levelling interrogates each pixel and auto determines if an inclined plane exists within the image. Given a small incline is often present due to the focusing requirements of white light interferometry the leveling feature is used to compensate for any potential incline. The zero fixing function simply offsets the image such that the minimum pixel value is set to zero. While not necessary for relative measurements across a given image, the zero fixing is a useful feature when comparing absolute values across images.

Figure 4 illustrates a typical captured image and accompanying measurements for a single location on a given part. The captured image shown top left of Figure 4, represents the raw image data acquired from the WYKO white light interferometer. The red areas shown, represent null or unrecorded data. These null data points are typically on the order of 2-5% of the overall image (3.2% in the case of Figure 4) and are ignored for all measurements. In order to overcome small areas of null data, and to obtain a more representative measure of the surface, profiles A-C are average values over a band of width 30 pixels.

As a direct result of the manufacturing process, namely interference between adjacent print jets along the print head, a pseudo sinusoidal surface profile running normal to the print head traverse direction is produced for all parts. This periodic effect can be seen from the raw 'Texture' profile shown in Profile A (Figure 4). This profile is in contrast to those shown in Profiles B and C where no periodic nature is observed and peak to peak magnitude of the measured profiles is less than that observed for Profile A.

In an effort to characterise this periodic effect, for each profile taken, measures of roughness (Ra) and waviness (Wa) were recorded. In effect, a filter was applied to the Texture data (black line) shown in Figure 4. The low frequency component, termed waviness (shown in red), can be considered as the overall surface profile and the high frequency component (shown in green) can be considered as roughness of the part. The distinction between the two terms can be readily observed from Profile A shown in

Figure 4. Roughness profiles were also captured along the valley (Profile B) and peaks (Profile C) of the wave nature of the surface in an effort to ascertain if any differences in roughness occur between valleys and peaks of the surface. In total, three measurements were taken along each direction, on each part, across all four parts in each material.

Results

Dimensional Accuracy.

Figure. 5 shows the mean and standard deviation for dimensional depth and height profiling for each of the three materials. Figure 5(a) shows the measured height for positive features printed in the direction of print and normal to the direction of print. Figure 5(b) shows measured depth measurements for negative features types printed in the direction of print and normal to the direction of print. The desired depth/height is of each feature is 500μm, as indicated by the dashed line. While the negative features are in agreement with the designed part depth, the positive features, independent of feature orientation relative to the traversing of the print head, are less than the desired height of 500μm. This deviation from the desired height is on the order of 3-7.5 % across all materials. This could, at least in part, be attributed to the viscous nature of the photopolymer. As each layer of a given positive feature type is printed, there is potential for the partially cured photopolymer to flow across the surface of the part, resulting in reduction in the original layer thickness. This effect, compounded layer on layer, could potentially result in a measurable reduction in desired feature height.

While the accuracy of the feature depth/height appears independent of the orientation of the feature relative to the print head traverse direction, the same cannot be said for feature width measurements. Figure 6 shows the mean and standard deviations of measured widths for positive and negative features aligned with print head traverse direction, and normal to print head traverse direction in all three test materials. The graphs demonstrate the impact of the print direction on the lateral dimensional accuracy of a given feature. Of particular note are the data from negative feature types, printed normal to the direction of print (Figure 6 (c)). The mean error between measured and desired width ranges from approx. 7 – 14%.

Roughness Measurements.

Figure 7 shows the mean and standard deviation of both roughness and waviness values for all three materials as measured along selected line profiles previously described. Across all materials the highest roughness occurred along the valley of the wave profile generated as a result of the manufacturing process. The roughness values for profiles taken normal to print head traverse direction and along the peak of the wave profile generated were comparable in the case of MED60 and RGD525. However, in the case of Vero White the roughness along the peak of the wave profile was comparable to that along the valley of the wave. This is in contrast to MED610 and RGD525, the reasons for this are unclear. Across all materials and directions characterised, the measured values of roughness range from approximately 0.2 – 0.45 µm and compare favourably with previously published data for alternative materials using PolyJet technology [14].

In terms of waviness, the waviness values normal to the print head traverse direction significantly exceed those waviness values measured along the print head traverse direction. Comparing all material graphs in Figure 7 it can be seen the characteristic surface feature normal to the print head traverse direction is waviness. While the nature of the waviness can be attributed to the manufacturing technique, it remains a defining surface feature and may be a consideration when producing parts using PolyJet technology.

Discussion

In terms of dimensional accuracy of a given part, it was found that both the orientation of the part relative to the print head traverse direction and also the nature of the features printed, be they in the positive or negative feature types, play an important role in determining the dimensional accuracy of the features.

In terms of feature depth/height, the orientation of a feature relative to the traverse direction of the print head proved significantly less important than the positive or negative nature of the feature. For both orientations of the feature, it was found that the positive feature height was lower, across all materials, than specified in the original design. It should be noted that based on the manufacturers specifications, the Objet 260 Connex 1 is capable of printing minimum layer thickness, of 16 μm [10]. Based on this value it can be considered there is good agreement between desired and actual dimensions for the negative features. However, in the case of positive features, the measured height was in all cases greater than 16 μm from the desired height. Considering that both positive and negative feature types were printed as part of the same production run, and given the accuracy of the negative feature depth, the observed discrepancy between measured and desired feature height could potentially be addressed from a software/firmware perspective.

It was found for optimal lateral dimensional accuracy the key dimension of a given feature should be placed normal to the direction of traverse of the print head. If this orientation is maintained, the nature of the feature in terms of whether the feature is positive or negative becomes less relevant. However, for many practical parts there may be a number of key features in various directions requiring stringent dimensional tolerances so this constraint may not be feasible.

For feature types with a key dimension along the direction of traverse of the print head, positive features were, in general, found to be smaller than designed while negative features were, for all materials tested, found to exceed the designed dimension. In relation to the manufacturers specifications, Stratasys indicate an accuracy of 20-85μm for feature sizes below 50mm [20]. Based on the manufacturer specifications, the MED 610 material can be considered to be within specification for all feature types and orientations measured. However, in the case of negative features printed normal to the traverse direction of the print head, the mean values of Vero White and RGD 525 were found to be outside the maximum described 85 μm tolerance by 49 μm and 57 μm respectively. These values represent deviations from the manufacturer's specification on the order of 50%.

In terms of surface profile, the waviness surface characteristic is a direct result of the manufacturing process and the waviness runs normal to the print head traverse direction. The roughness of the part varies between wave peak and wave trough. However, for many engineering applications sub-micron Ra values are often acceptable. Further, in terms of the use of PolyJet printing for the manufacture of functional components, many manufacturing processes, for example casting, often require some level of post processing of parts. Should either the dimensional accuracy or surface profile of a given part not be acceptable for a given application, there is potential for PolyJet printing to be used in conjunction with a more traditional, typically subtractive, manufacturing technique to further improve the part quality in terms of its physical appearance. Given the similarities of all results across all three material types measured in this work, the limitations of dimensional accuracy and surface profile can be largely attributed to the limitations of the process hardware and software as opposed to inherent limitations of the materials themselves. Given the trend in increased precision in instrumentation at reducing costs, there is scope for further improvements using the underlying principle of PolyJet technology.

Dimensional accuracy depends largely on the speed of polymerisation and the viscosity of the photocurable resin material. In the case of the Objet Connex, the time between ink-jetting and curing steps determines the level of resin relaxation/leakage with longer times leading to a reduction in dimensional accuracy. This can be mitigated by using the gel-like support material to contain the uncured resin material between ink jetting and curing steps, using the “matt” surface setting. This was not investigated in this work but preliminary data suggests that this is the case.

Conclusion

This paper describes the potential of a high end commercially available additive manufacturing machine (Objet 260 Connex1) to produce functional parts. The paper focussed on the current capabilities of existing hardware as opposed to the theoretical potential of the additive manufacturing technique. Three alternative materials across the product range were tested in terms of dimensional accuracy and surface finish. Particular attention was given to the build orientation of the parts. It was found that build orientation can have a significant impact on the dimensional accuracy of features contained within a part and this trend was observed across all materials. Further, in terms of surface profiling, the dominant waviness feature of the surface is as a direct result of the nature of the manufacturing process.

However, results across all materials tested were relatively consistent. This indicates the current limiting factor for the Objet 260 Connex 1 lies within the machine hardware/software as opposed to the materials themselves. While the dimensional accuracy and surface profiles may be acceptable for certain applications, it would be expected that any improvements in the Objet range of machines would results in improvements on the dimensional accuracy and surface finish of printed parts.

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Figure 1. The PolyJet 3D printing technique. Liquid photopolymer and support material are deposited on to the printer bed (A) and subsequently cured using an ultraviolet (UV) lamp (B).

Figure 1. Test part used in the evaluation of the Objet 260 Connex 1. Piece consists of positive and negative feature types, normal to and aligned with print head direction along with an area for surface profile measurement.

Figure 2. Stitched images and corresponding data from the Keyence VHX2000E. Stitched images are shown in 3D and plan view with indicative line profiles (A). A sample line profile used to determine dimensional integrity of the test piece (B).

Figure 4. Image acquired using WYKO NT1100 and corresponding line profiles taken at various locations across the part represented by Profiles A-C. The raw 'Texture' data shown in black, consists of a Waviness profile (red plot) and surface roughness (green plot).

Figure 5. Measured height and depth profiles for positive and negative feature types, printed in all materials. Figure 5 (a) shows height profiles for features printed normal to, and aligned with, the traverse direction of the print head. Depth profiles for features printed normal to, and aligned with, are shown in Figure 5(b). The dashed line on both figures indicates the height/depth set point.

Figure 6. Plots showing the mean and standard deviation of widths of positive and negative feature types printed normal to, and in the direction of print head traverse direction. Figure 6 (a-b) shows results from positive feature types normal to, and aligned with the direction of traverse of the print head respectively. Results from negative feature types normal to, and aligned with the direction of traverse of the print head are shown in Figure 6 (c-d). The dashed line represents the dimensional set point.

Figure 7. Measured roughness (Ra) and waviness (Wa) values for each material measured normal to the print head traverse direction (Normal). Valley and Peak measurements represent measurements taken along the direction of print head travel. Valley measurements as shown represent measured values along the valley of the wave. Peak profile measurements are taken along the peak of the wave profile.

Figure 1

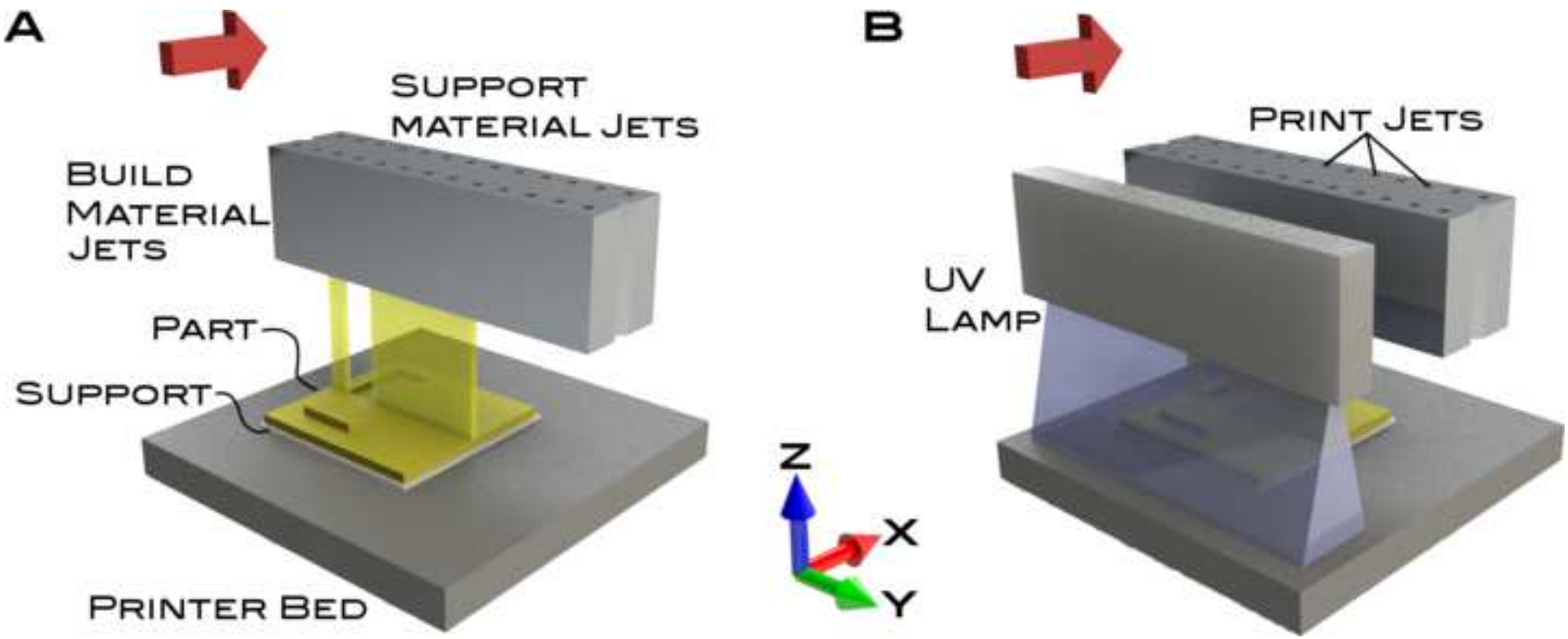

A
Support
Material Jets
Build
Material
Jets
Part
Support
Printer Bed
Z
X
Y
B
Print Jets
UV
Lamp

Figure 2

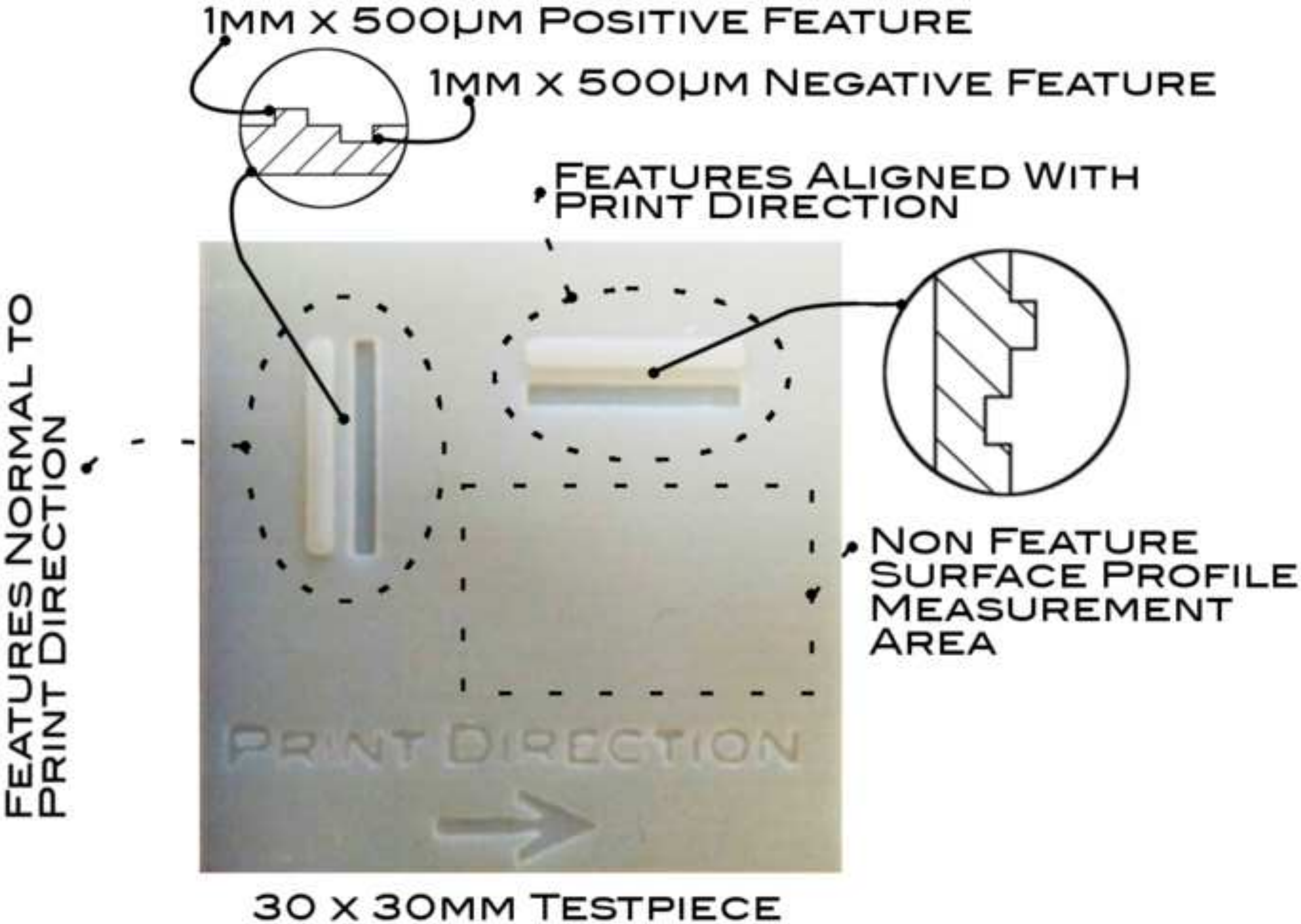

1mm x 500µm Positive Feature
1mm x 500µm Negative Feature
Features Aligned With Print Direction
Features Normal to Print Direction
Non Feature Surface Profile Measurement Area
Print Direction
30 x 30mm Testpiece

Figure 3

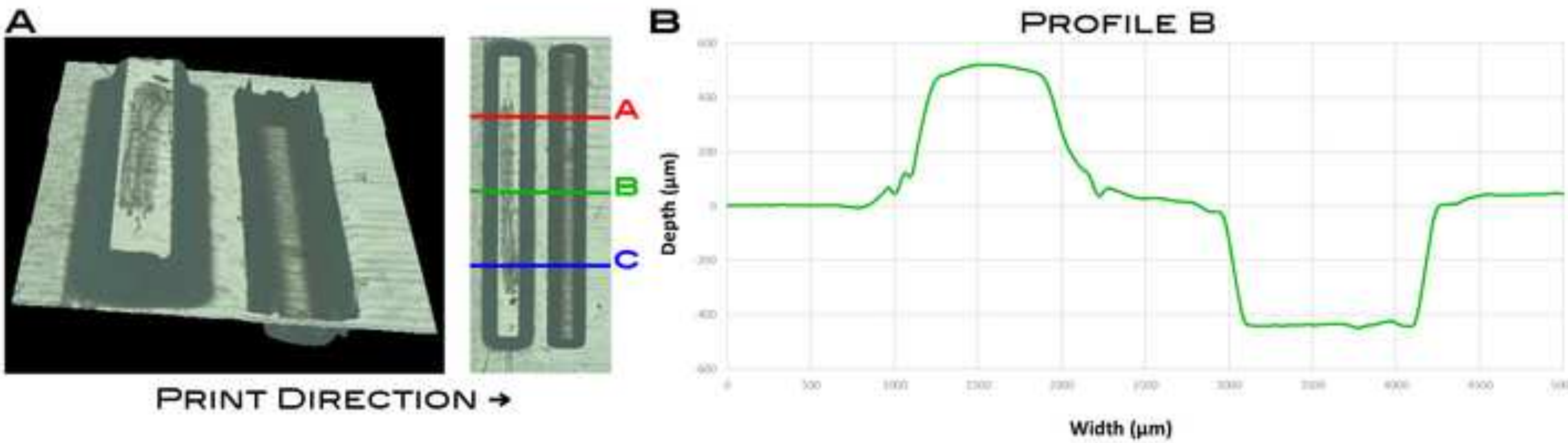
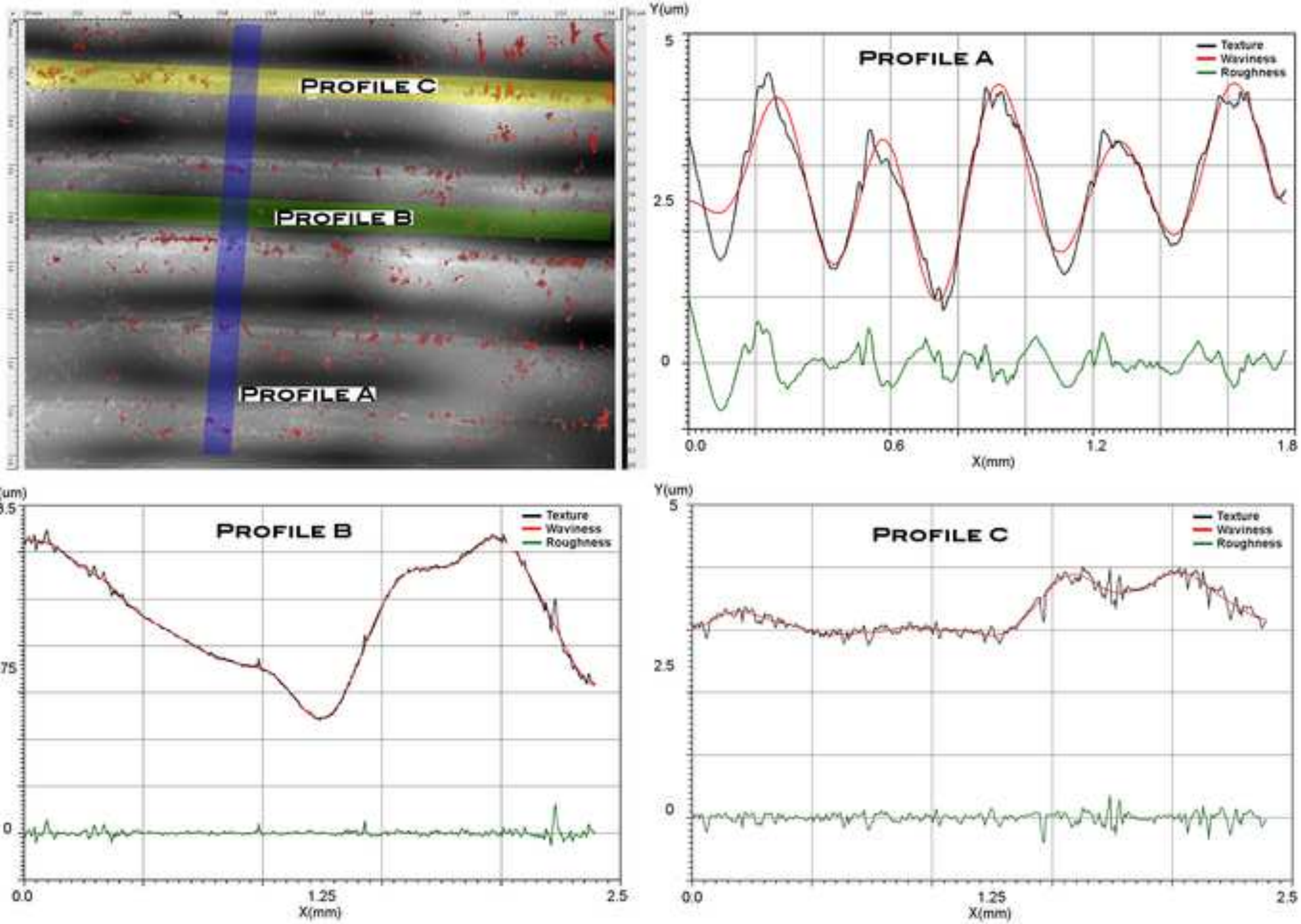
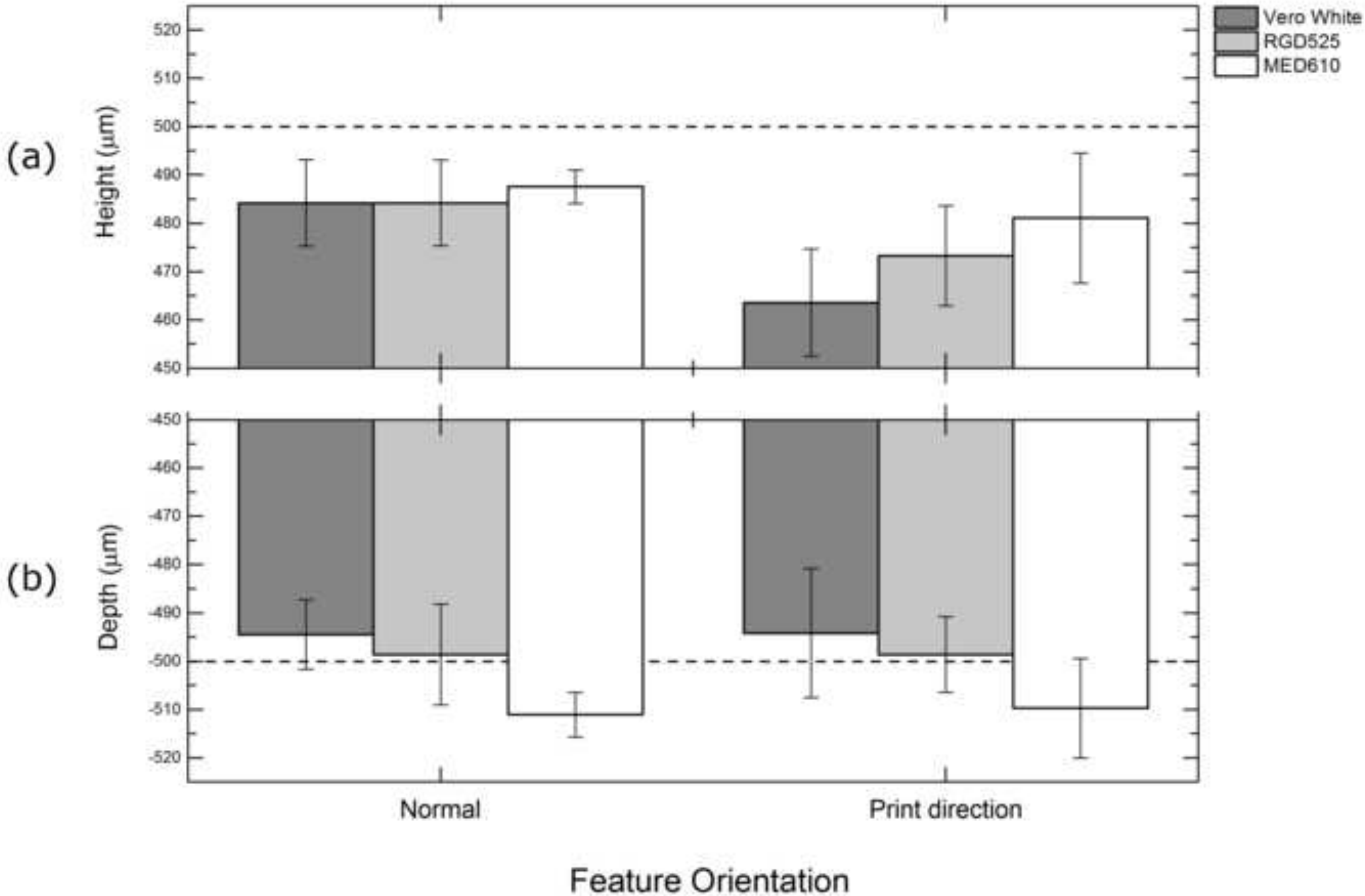


Figure 4



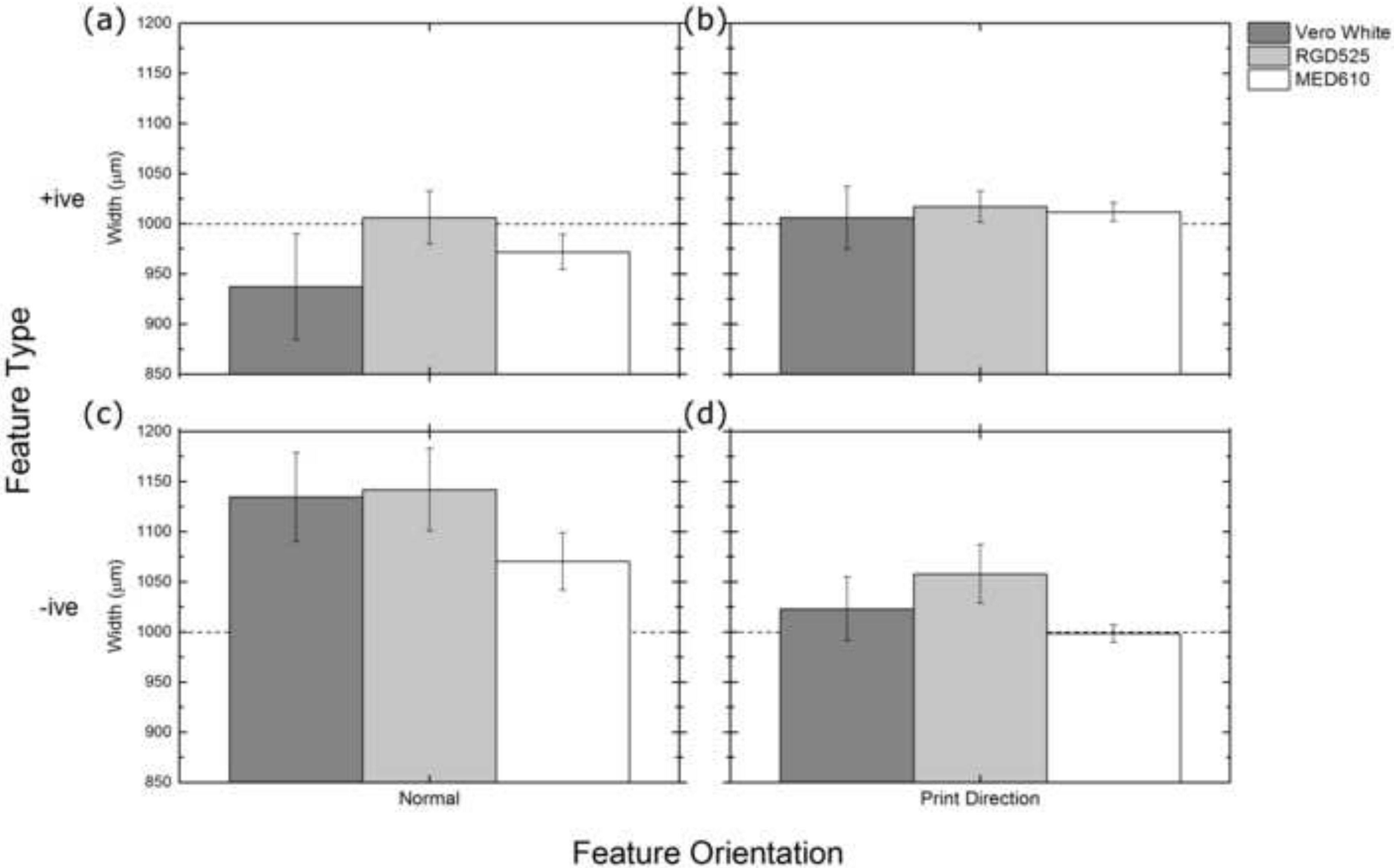
Profile C
Profile B
Profile A
Y(um)
Texture
Waviness
Roughness
X(mm)

Figure 5



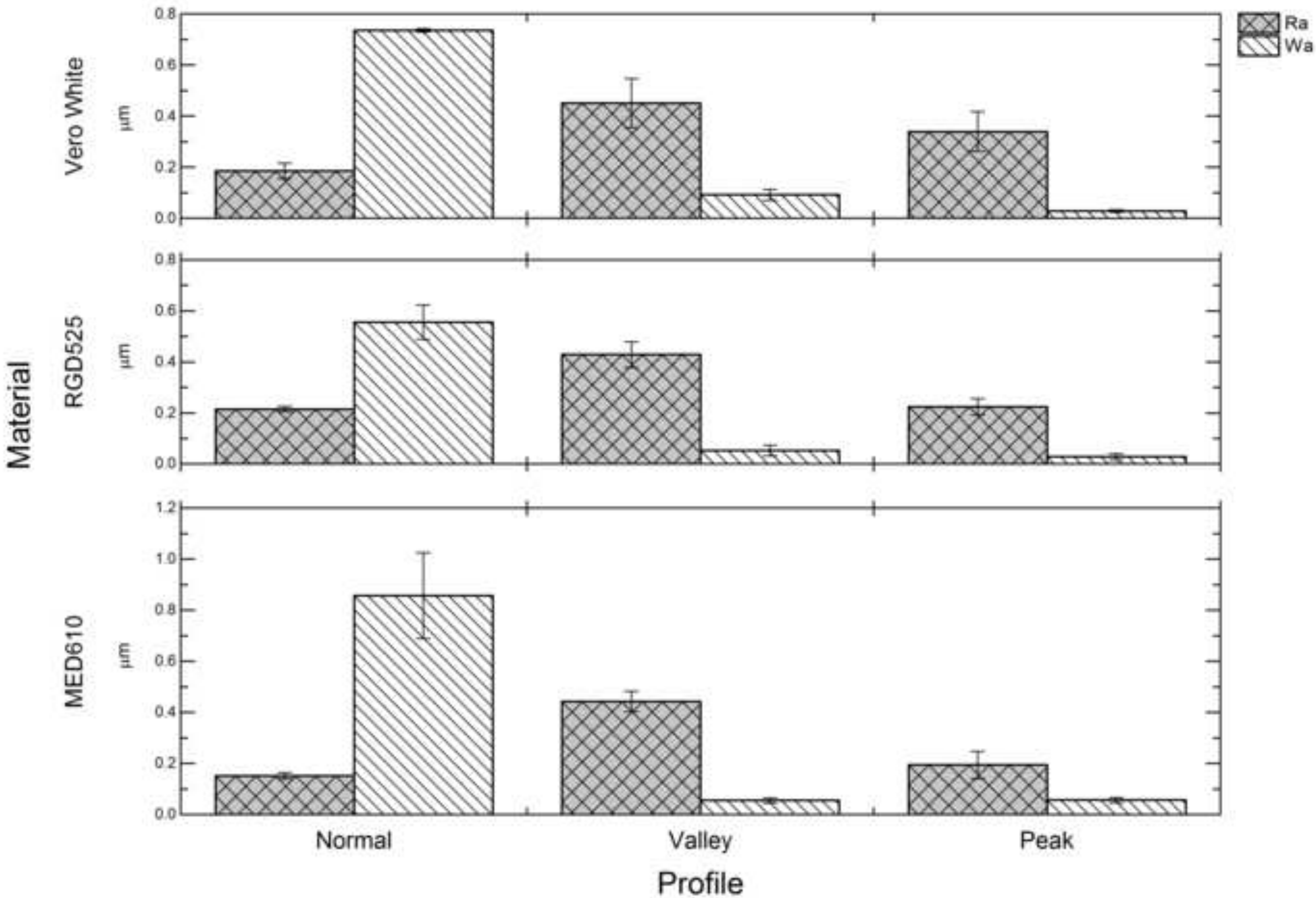
Vero White
RGD525
MED610
(a)
Height (μm)
520
510
500
490
480
470
460
450
(b)
Depth (μm)
-450
-460
-470
-480
-490
-500
-510
-520
Normal
Print direction
Feature Orientation

Figure 6



(a)
(b)
(c)
(d)
Vero White
RGD525
MED610
+ive
-ive
Width (μm)
1200
1150
1100
1050
1000
950
900
850
Feature Type
Normal
Print Direction
Feature Orientation

Figure 7


Ra
Wa
Vero White
RGD525
MED610
Material
µm
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Normal
Valley
Peak
Profile