Quality of Parts Processed by Fused Deposition

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Abstract.

FDM™ (fused deposition modeling) is a SFF technique for the fabrication of polymer parts. Research is being conducted on the fabrication of ceramic parts by fused deposition. In this study polymer and ceramic parts were made using a commercially available FDM™ system, 3D Modeler, and the Quickslice™ software. These parts were evaluated for processing defects.

Defects originate from the fused deposition process, from material characteristics, or a combination thereof. Process defects, which are present in all polymer parts, are due to current hardware, software and build strategy limitations. These same defects are seen in ceramic parts fabricated by fused deposition of ceramics (FDC). Another set of defects in ceramic parts is due to materials characteristics, i.e., non-uniformities in the feed stock filaments, their mechanical and/or rheological properties.

The presence of defects in polymer or ceramic parts was studied using simple build primitives (single roads) and parts in the green state. Parts were characterized for their quality using SEM and optical microscopy.

Introduction.

In terms of product development, the fabrication of a design prototype is one of the most time consuming and expensive steps in manufacturing. Over the last few years, several new techniques have been developed, whereby a CAD file of a design is used to manufacture a functional model by an 'additive' process rather than the normal subtractive process, where a block of material is taken and anything that is not needed is cut away. Such a functional prototype will aid in the identification of design errors, and improvements through rapid feedback with design teams can reduce the prototype cycle by more than 90 %. These techniques are invariably called rapid prototyping or solid freeform fabrication. More recently, these techniques have not only been used for prototype fabrication, but also for manufacturing of small production runs and fabrication of molds, dies and other tooling.

Several rapid prototyping techniques have been developed, such as selective laser sintering (SLS), direct light fabrication (DLF), layered object manufacturing (LOM), 3D printing, stereo lithography (SLA), fused deposition modeling (FDM), etc. Some of these techniques have become commercially available. Although some of these originated for fabrication of polymer parts, there has been a large effort to use these techniques fabricate metal, ceramic, and composite parts [1,2,3]. DLF, 3D printing and especially SLS have shown very good progress in fabricating metal or ceramic parts.

Stratasys Inc. has developed fused deposition modeling (FDM™), whereby thermoplastic materials are extruded through a nozzle into thin roads [4,5]. The thermoplastic solidifies rapidly upon deposition, and the part is built from the bottom up, layer by layer. Stratasys has developed various materials systems for the fabrication of polymer parts.

Agarwala et al. have shown the feasibility to use FDM to fabricate advanced ceramic parts, the fused deposition of ceramics (FDC) [6]. The FDM™ system uses a 0.070" filament as feed stock. Ceramic feed stock was obtained by dispersing 60 vol.% Si_3N_4 powder (AlliedSignal's GS44 Si_3N_4 powder) into an appropriate binder system. The filaments are fabricated either by capillary or twin screw extrusion, after which a part is built by FD. The organic binder is subsequently removed and the part is densified. A similar technique for the fabrication of metal parts was recently developed by Greulich et al. [7].

The fabrication of both polymer and (green) ceramic parts using FDM leads to the presence of a unique set of defects. This is not only due to hardware and software related issues but also feedstock material characteristics. In the case of ceramics, it is imperative to determine the causes for these defects, since they will only worsen during binder removal and sintering and have adverse effects on the mechanical properties.

Experimental

The FD process starts by designing the part on a CAD workstation using a suitable CAD package (I-DEAS, Camand, Pro-E). This design is then imported into the slicing and tool path generating software (Quickslice™ or Protoslice™) which slices the design mathematically into layers. This program then creates the deposition paths or roads. The Quickslice™ software controls the motion of the nozzle and the motion of the feed wheels (for a more detailed description of this process, please see Comb et al. [5] and Agarwala et al. [6]). In general, the outer perimeter of the part is laid down first , after which the 2D plane is filled. Several different filling strategies are shown in Figure 1. Only the raster filling will be used in this study (Fig. 1a). The layers are deposited consecutively at a 90° angle to the previous one to improve homogeneity.

For proper plane or volume filling, the characteristics of the hardware, such as the nozzle diameter, must be considered when the slicing routine and toolpath are generated. If, for instance, a road width is chosen that does not match the nozzle size, this will lead either to gaps or too much material being deposited. Generally, the firmware sets certain default parameter values, once the nozzle diameter is chosen. During deposition, the nozzle needs to move very efficiently in the x and y direction to assure an uniform road width. However, at the start and stop of a road, the nozzle and material flow needs to be controlled even more accurately to ensure complete filling.

Both polymer and green ceramic parts were built using various build strategies. For the polymer parts, several of the Stratasys' systems were used, such as investment casting wax, machinable wax and Nylon P301.

The fabrication of the FDC feed stock filament is discussed in detail elsewhere in this volume [6]. To study the homogeneity of the particle dispersion, both single roads (extruded through the FDM nozzle) and the starting ceramic filaments were studied using SEM. The green parts were examined optically and by SEM. SEM analysis was done on an Amray 1400 at 20 kV. The samples were coated either with Au or C for backscatter analysis. No beam effects were observed during the SEM analysis.

Results and Discussion

Parts manufactured by the incremental addition of material suffer from a class of build defects that are generally unique to these processes. Roughly, these can be classified into two separate sets: surface defects and internal defects. The characterization and study of defects in the rapid prototyping field have concentrated largely on surface defects. The use of models for prototype and pattern purposes require a smooth surface.

For the manufacture of functional components, however, internal defects are an additional concern.

Surface Defects

Two common surface defects are the staircase and chordal effect. The stair case effect is a common effect of most RP methods and is caused by the slice method of manufacturing. Methods of treating this effect range from varying the thickness of the slice [8] to intermediate processing [9]. The former reduces the scale of the error without really eliminating it. From a study of current processes, intermediate (or post) processing seems still to be a required way to address this problem.

The chordal effect originates in the "stl" format files that are commonly used by most RP methods. The "stl" files approximate surfaces as a web of triangles. All curvilinear surfaces are thus approximated as a series of linear segments leading to a non-smooth surface of the part. Apart from selecting a different surface modeling format, the temporary solution may simply be a positive offset to the part and then a post-process finishing. However, the original curve of the surface may never be recovered.

Other surface defects include the support structure burrs, start/end errors and the ridged top surface due to the deposition of the arc shaped roads.

Internal Defects

Internal defects in polymer and green ceramic parts arise due to a mixture of hardware and software limitations and materials characteristics. Sub-perimeter voids (Figure 2a) are caused by the incomplete filling of the area inside the perimeter of the FD part. At the point where the path of the FD head approaches the perimeter, the travel direction of the FD head alters to a path that is tangent to the perimeter. The result is an insufficient material flow to fill the volume at these intersections leading to a void. Methods of solving this problem range from giving a negative offset to the perimeter and/or increasing the flow rate at the points of intersection. The size of the sub-perimeter void varies with the position along the perimeter. Figure 3 is a SEM micrograph showing the presence of sub perimeter voids in a Nylon P301 part in the x, y build plane. However, by carefully changing the process parameters it is possible to remove these defects altogether, as can be observed in Figures 4 and 5. This shows that the process can be optimized and that these unique defects can be removed without changing any of the hardware or the necessity of using any post processing steps.

Inter-road voids and road thickness variation defects (Figure 2b) are caused by inconsistent material flow due to both slipping in the filament feed mechanism (rollers) and variations in the filament diameter. With tight filament diameter control and better gripping rollers, these defects can be minimized or eliminated. Tool paths with long vector lengths could lead to incomplete inter-road bonding due to substrate cooling. The inter-road voids are rarely observed in the FDM or FDC samples. Similar inter-road delaminations can arise when the different roads do not bond. These defects are analogous to the knit lines in injection molded ceramic parts. Improving inter-road bonding through the use of tackifiers in the binder composition may help to prevent these defects.

Inter-road type errors also occur when non-convex areas (Figure 6a) are rastered by discontinuous fill patterns. These discontinuous fill patterns occur because the software cannot process vector segments at intersections of the raster with perimeters that the raster is tangent to. This is true of simply connected concave areas and of multiply connected areas. In the latter case, the internal holes are responsible for the tangential intersections. As a result of this segmenting of the raster fill, an error is caused along the knit line between one segment and another (Fig. 6a, arrows). This causes problems of cracking during binder removal and sintering. The solution is to change the fill pattern or to locally heat the substrate or increase the flow of material.

Core voids (Fig. 6b) are caused when an incorrect road width is selected for the contour fill of an area. In the figure shown, if the thickness of the C-section was 65 mil and the road widths were 10 mil, a 5 mil void would be left along the center. The solution is to determine the closest road width to the ideal with an increased flow in the final contour to fill in the void.

FDC Feedstock

Most of these specific defects are unique to the FDM and FDC processes due to the hardware limitations (nozzle shape and size), software limitations (build strategy) and materials characteristics (set time, rheology, tackiness etc.). Optimization of the feed stock is important to prevent any flow and fill non-uniformities. Other internal defects may arise if the feed stock is not uniform in dispersion or density, especially in the case of FDC.

FDC feed stock is a 0.070" ceramic powder filled filament that needs to have both uniform particle dispersion and dimensions. Capillary extrusion was used to fabricate 10-12" segments of filament with a variation in diameter of ± 0.001". However, between different segments, there was a spread in the diameter as large as 0.065-0.070". When used to make FDC parts, the diameter variation of the discontinuous filament led to internal defects as discussed above and by Agarwala et al. [6].

Figure 7 shows the fracture surface of a 0.070" FDC feed stock filament. The filament is uniform in shape and dimension, showing no defects, burrs or any surface non-uniformities. These micrographs also show a uniform dispersion of the powder in the polymer without any observable defects or non-uniformities. The measured densities by He pycnometry agree with the theoretically calculated values. There is no measurable porosity in the extruded filaments.

Figure 8 shows the single fracture surface of a 0.037" FDC road. The roads are uniform in dispersion, but the road shape and surface show non-uniformities. The FDM machine uses aluminum nozzles for the extrusion of the polymers. These nozzles were also used for FDC. Optical microscopy of these nozzles and comparison with new nozzles showed that substantial wear had occurred. This will require the substitution of hardened materials for the FDC nozzles.

Summary

The fabrication of polymer and ceramic parts has been demonstrated using the FD technique. The current FDM process leads to a unique set of internal and surface defects. However, through careful process parameter control, it is possible to make high quality parts. Areas of future optimization include improving surface finish through post processing steps and improvements in the system hardware and control software. Feed stock optimization is also critical as defects in ceramic filaments will result in defects and strength reduction in sintered ceramic parts.

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Literature

[1] D. L. Bourell, J. J. Beaman, H. L. Marcus, J. W. Barlow, "Solid Freeform Fabrication: An Advanced Manufacturing Approach," Solid Freeform Fabrication Symposium Proceedings, edited by J. J. Beaman, H. L. Marcus, D. L. Bourell, J. W. Barlow, Center for Materials Science and Eng., Univ. of Texas, Austin, TX, pp 1-7 (1990)

[2] R. I. Campbell, P. M. Dickens, "Rapid Prototyping: A Global View," Solid Freeform Fabrication: An Advanced Manufacturing Approach," 5th Solid Freeform Fabrication Symposium Proceedings, edited by H. L. Marcus, J. J. Beaman, J. W. Barlow, D. L. Bourell, R. H. Crawford, Center for Materials Science and Eng., Univ. of Texas, Austin, TX, pp 110-117 (1994)

[3] R. F. Aubin, "A World Wide Assessment of Rapid Prototyping Technologies," 5th Solid Freeform Fabrication Symposium Proceedings, edited by H. L. Marcus, J. J. Beaman, J. W. Barlow, D. L. Bourell, R. H. Crawford, Center for Materials Science and Eng., Univ. of Texas, Austin, TX, pp 118-145 (1994)

[4] R. Wales, B. Walters, "Fast, Precise, Safe Prototypes with FDM," 2nd Solid Freeform Fabrication Symposium Proceedings, edited by H. L. Marcus, J. J. Beaman, J. W. Barlow, D. L. Bourell, R. H. Crawford, Center for Materials Science and Eng., Univ. of Texas, Austin, TX, pp 115-122 (1991)

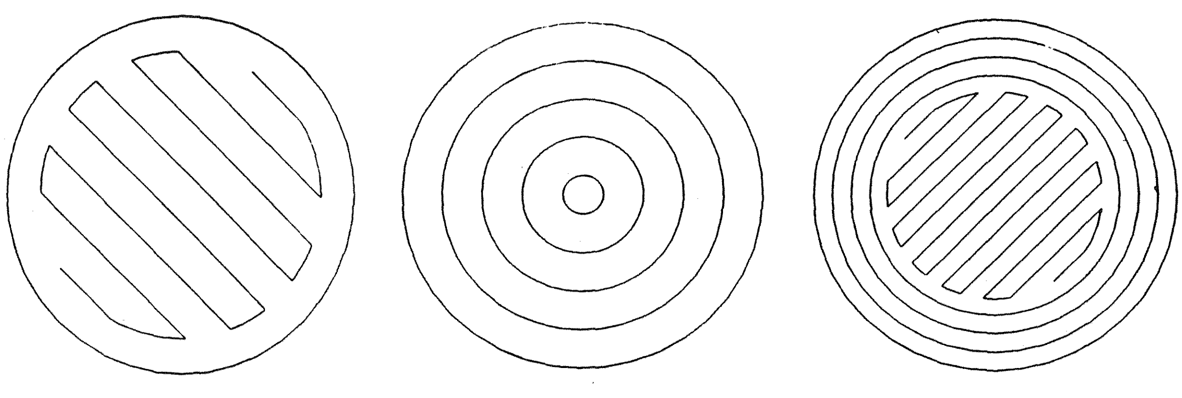
[5] J. W. Comb, W. R. Priedeman, P. W. Turley, "FDM Technology Process Improvements," 5th Solid Freeform Fabrication Symposium Proceedings, edited by H. L. Marcus, J. J. Beaman, J. W. Barlow, D. L. Bourell, R. H. Crawford, Center for Materials Science and Eng., Univ. of Texas, Austin, TX, pp 42-49 (1994)

[6] M. K. Agarwala, R. van Weeren, R. Vaidyanathan, A. Bandyopadhyay, G. Carrasquillo, V. Jamalabad, N. Langrana, A. Safari, S. H. Garofalini, S. C. Danforth, J. Burlew, R. Donaldson, P. Whalen, C. Ballard, "Structural Ceramics by Fused Deposition of Ceramics," these proceedings.

[7] M. Greulich, M. Greul, T. Pintat, "Fast, Functional Prototypes via Multiphase Jet Solidification," Rapid Prototyping Journal **1** (1), 20-25 (1995)

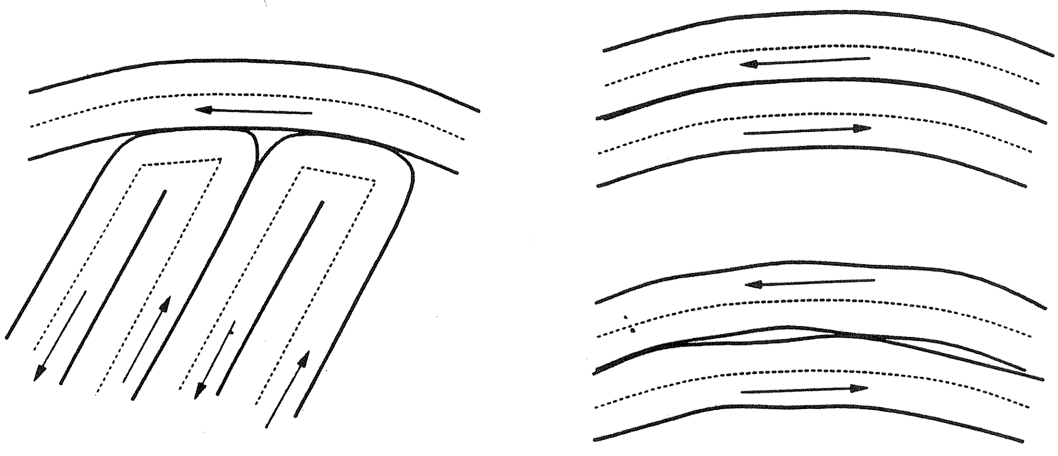
[8] R. Crawford, "Computer Aspects of solid Freeform Fabrication: Geometry, Process Control and Design, 4th Solid Freeform Fabrication Symposium Proceedings, edited by H. L. Marcus, J. J. Beaman, J. W. Barlow, D. L. Bourell, R. H. Crawford, Center for Materials Science and Eng., Univ. of Texas, Austin, TX, pp 102-112 (1993)

[9] R. Merz, F. B. Prinz, K. Ramaswami, M. Terk, L. E. Weiss, "Shape Deposition Manufacturing, 5th Solid Freeform Fabrication Symposium Proceedings, edited by H. L. Marcus, J. J. Beaman, J. W. Barlow, D. L. Bourell, R. H. Crawford, Center for Materials Science and Eng., Univ. of Texas, Austin, TX, pp 1-8 (1994)



(a) (b) (c)

Figure 1. Several different build strategies are possible to fill the 2D plane within the outer perimeter such as (a) raster fill, (b) contour fill and (c) raster/contour fill



(a) (b)

Figure 2. Schematic of the build strategy showing the (a) formation of the sub-perimeter void at the intersection of the perimeter and plane filling and (b) the formation of inter-road voids due to long vector lengths or non-uniformities in the filament

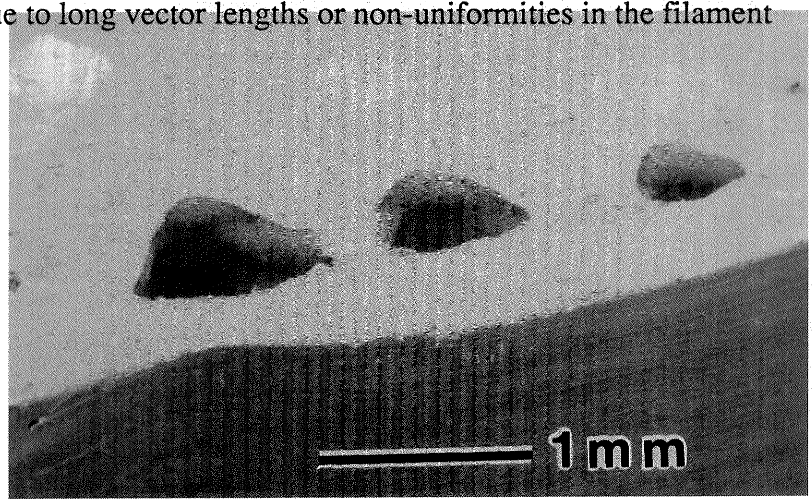


Figure 3. SEM micrograph showing the presence of sub perimeter defects (in the x, y plane) in a Nylon P301 FDM sample.

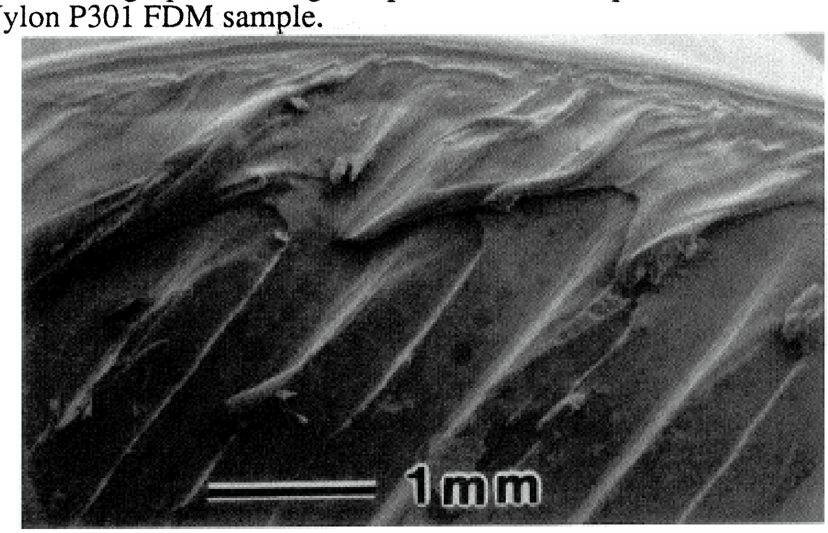


Figure 4. SEM micrograph of a green FDC sample showing that with careful monitoring of the process parameters, both the inter road defects and the sub perimeter defects can be removed.

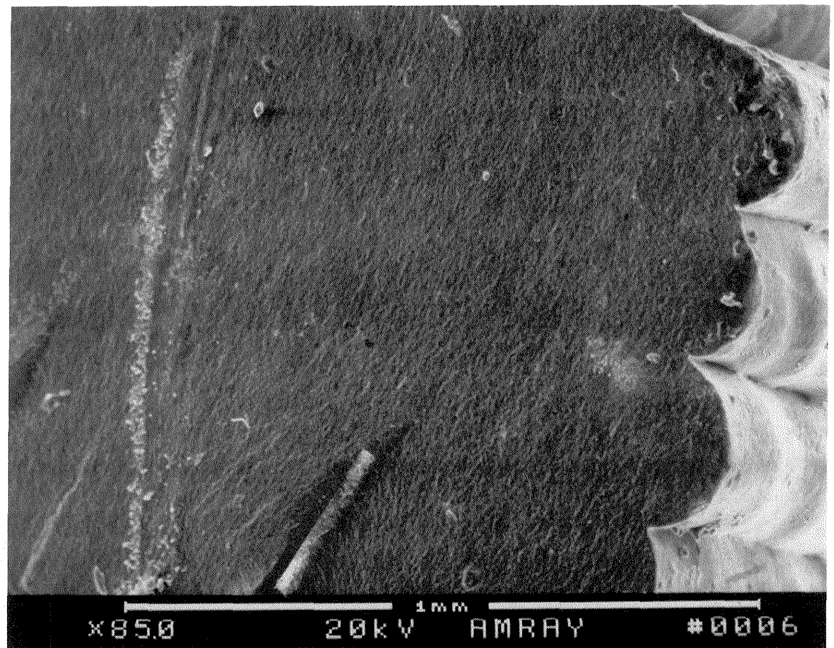
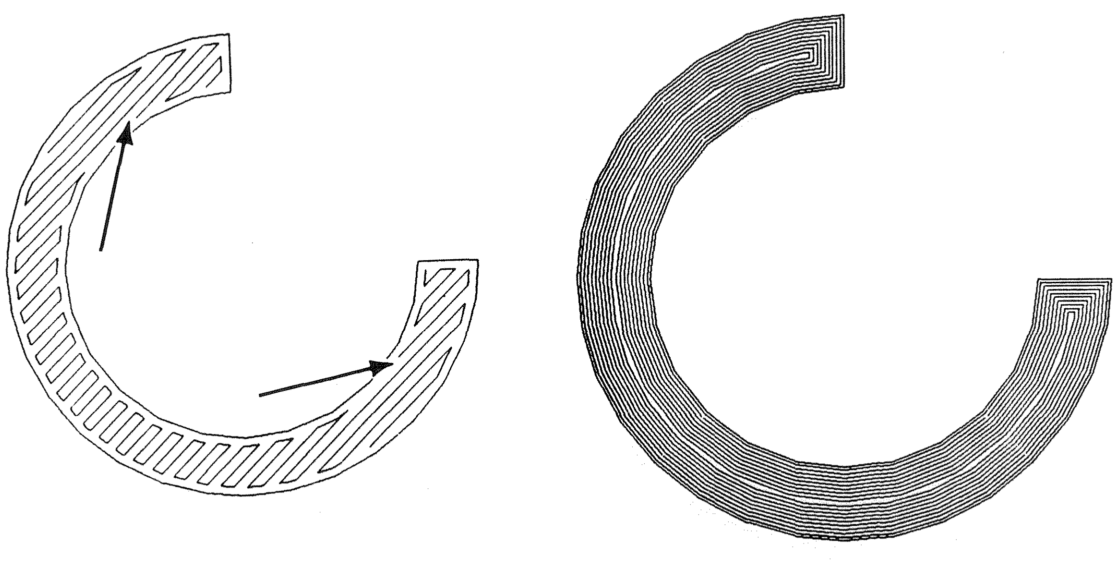


Figure 5. SEM micrograph of a cross section of a green FDC sample showing, similar to Figure 4, that with careful monitoring of the process parameters, both the inter road defects and the sub perimeter defects can be removed.



(a) (b)

Figure 6. Schematic showing the (a) formation of knit line errors (arrows) due to the discontinuous filling of the plane and (b) formation of a core void when an incorrect road width is used.

Figure 7. SEM micrograph of the fracture surface of a 0.070" green FDC filament fabricated by capillary extrusion, showing both a uniform shape and dispersion of powder/polymer.

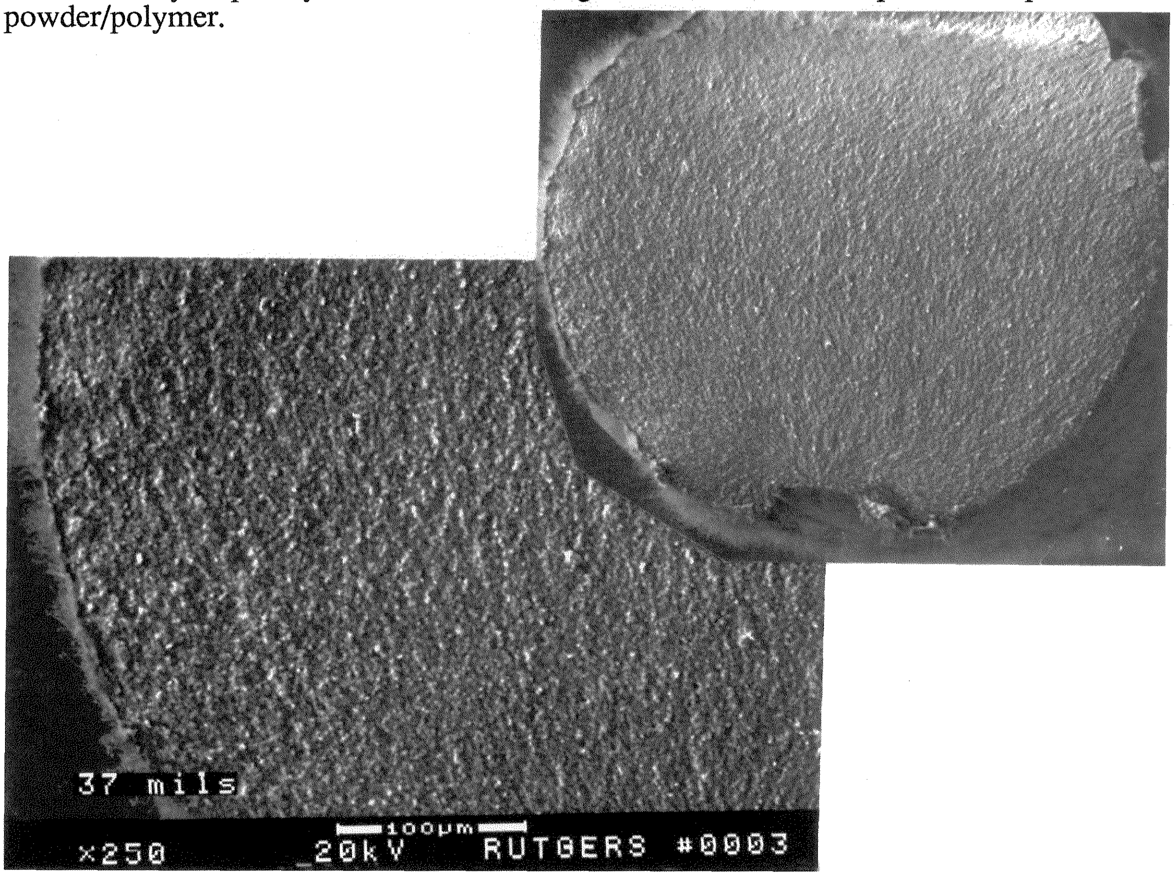


Figure 8. Backscatter SEM micrograph of the fracture surface of a 0.037" FDC single road showing a less uniform shape possibly due to nozzle wear (insert) but still a uniform dispersion.