FABRICATION OF CARBON-CARBON G RIDS FOR ION OPTICS

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Carbon-carbon composite ion grid blanks measuring 20 cm on a side and 0. S-1.0 mm in thickness were fabricated from laminated plies of unidirectional carbon. carbon tape. Plate flatness varied by less than ± 0,0S mm. The screen grid panels and the acelerator/decelerator grid panels were formed from six and twelve laminated plies of unidirectional tape, respectively, No delamination of the plies waso observed following the processing procedures. Materials proprties of the panels are superior to those obtained from carbon-carbon panels created from fabric. To increasefinal grid strength, the tape plies were oriented to minimize the number of fibers that will be cut when the ion extraction holes are machined. Several methods were investigated for forming ion extraction apertures In the carbon-carbon plates, Including electric discharge machining, ultrasonic impact grinding, laser machining, water jet etching, and sandblasting. Only EDM and ultrasonic etching appear feasible for machining high open area screen grids; both techniques are costly. Recent successes in mechanical machining of thin, dished graphite grids or use of non-circular hole geometries may reduce the cost of machining the ion extraction apertures.

INTRODUCTION

'1'here is increasing interest in developing propulsion systems to enable planetary missions to be performed on smaller launch vehicles to reduce costs. Ion propulsion is a technology which can achieve the goal of performing meaningful planetary exploration missions with very small launch vehicles.[1,2] Numerous mission analyses have shown that the use of ion propulsion significantly benefits planetary exploration and lunar/Mars piloted anti cargo missions.[3-5]

With limited launch vehicle payload envelopes and mass margins, it is aiso desirable to m inimize both the. volume and mass of ion propulsion systems. Onc approach to accomplish this is to minimize the number of engines required to perform missions of interest.

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The number of engines required in an ion propulsion system is determined by the power which can be processed by each engine, and by the useful engine life. time. "1'0 minimize the number of engines required 10 perform a mission there.fore necessitates the development of engines which operate at higher power levels and/or for longer periods of time.

The performance of an ion thruster depends chiefly on the design and performance of the, ion extraction grids. The problems inherent in increasing tbc thrust density and total thrust of an ion engine arc grid erosion and the.rmai (i istortion which changes the grid separation distances. Grid erosion, duc to ion sputtering of the grid surfaces by discharge chamber or charge-exchange ions, becomes more severe as the thrust density increases because the ion flux 10 the grids increases. Thermal distortion results from non-uniform hc.sting of the grid electrodes in the form of radial and grid-to-grid temperature gradients.

Test data[6] indicate that ion engine operating life is limited by sputter erosion of the ac.c.c.lc.rater grid by charge-c.xchange ions. in this test, pits were erode.d completely through the molybdenum accelerator grid in icss than 895 hrs. Grid life in spat.c,-like conditions was extrapolated to be in excess of 11500 hrs[6]. However, more recent analyst.s concluded that the in-space grid life was probably less than or equal to 6,000 hrs[7]. Data from an extended test of a 6-kW argon ion engine recently completed at JP1, that utilized a negatively-biased decelerator grid[8] indicates that grid life may be significantly increased with this technique, but the magnitude of the reduction in erosion in si]acc-like conditions has not been verified.

Presently, state-of-tile-ari grids are fabricated from mol ybdenum sheets. Carbon-carbon may be superior to molybdenum for usc as a grid male.riai[9]. The materials properties of carbon-carbon can be modified to provide a near-zero coefficient of thermal expansion over a temperature range of approximately 0-800 K. This means that (be. grids may not distort thermally as much as dished molybdenum grids. in additon, hole alignment between the screen, accelerator, and decelerator grids may therefore be superior, resulting in higher thrust densities. Finally, based on sputter yield data, a grid fabricated from carbon-carbon may be expected to wear at a rate, of 20% compared to mol ybdenum,[1]() assuming carbon-carbon erodes at rates simialr to graphite.

Carbon-carbon composites[11-1]7, or carbon fiber reinforced carbon composites (CFC), are defined as structures consisting of fibrous carbon substrates in a carbonaceous matrix[14]. Carbon-carbon composites combine the desirable. male.riais properties of carbon and graphite with the strength provided by weaving carbon fibers into an integral structure. Additional strength and mechanical stability is added when a matrix of carbon is incorporated into the structure by liquid impregnation or chemical vapor infiltration processes. Conventional CFC structures have specific strengths of approximately 70% of refractor y superal ioys at moderate temperatu res.

One potential limitation of carbon-carbon for ion extraction grids is a lower flexural modulus compared to molybdenum. To overcom this it may be necessary to increase the thickness of the grids and reduce tile grid-to-grid spacing. This results in an increase in the electric field stress between the grids relative 10 molybdenum panels. In addition, large numbers of fibers arc cut when the ion extraction holes arc machined, furthur reducing the strength of the carbon-carbon panels. The holes themselves arc inexpensively machined in molybdenum using chemical etching, but costly techniques such as electric discharge machining (EDM) may be rused to fabricate holes in carbon-carbon.[9]

This paper presents the preliminary results of an experimental evaluation of carbon-carbon composite panels fabricated from unidirectional tape. The materials properties of the. carbon-carbon panels will be presented and compared to mol ybdenum. Plate fabrication and hole fabrication procedures will also be discussed.

CARBON-CARBON 'ANEL FABRICAT ON

Fabrication:

Panels 20 cm x 20 cm were fabricated from unidirectional plies of DuPont E55 carbon fiber. The E55 pitch-based carbon fiber was selected both because a supply of the material was on hand, and because earlier testing of this fiber showed that the modulus of elasticity of the fiber was readily increased by heat treatment up to a value of 140 MSi, which is the theoretical maximum value for graphite.

Carbon tapes were made by winding the E55 fiber with phenolic resin onto drums. Individual layers of tape were subsequently laminated into preforms. The screen grid preforms were laminated from six layers oriented [0/+60/-60/-60/+60/0], and the accelerat or/decelerator decel gri d preforms were lam inated from twelve layers oriented as two screen grids back to back, The tape plies were made as thin as possible so that the layup would be balanced in order to avoid distortion duc 10 processing stresses. Typical screen grid panels were 0.5 mm thick, and accelerator/(icccleralor panels were approximately 1.0 mm thick. 1,an]ina[ion/cure was performed in an autoclave. The carbon/phenolic preforms were then processed into panels using several carbonization, graphitizat ion, and chemical vapor infiltration (CVI) techniques. A major concern was that the panels would delaminate at the temperatures used in the processing, however, this did not occur,

Panel Material Properties:

At this time only preliminary mechanical test data arc available for this material. initial tensile test data arc compared 10 data for woven cloth from Ref. 9:

Property	Value, MPa	
	Woven cloth	Unidirectional tape
Tensile Strength:	119	310
Effective Fiber Strength:	-	2233
Fiber Strength Efficiency:	-	0.(fin
Tensile Modulus:	97,216	137,895
Effective Fiber Modulus:	-	1,006,663
Fiber Modulus Efficiency:	-	1.13*
Flexural Modulus:	171,680	-

The effective fiber strength and modulus are obtained by normalizing the composite properties by both the fiber volume and the fraction of fibers in the test direction. The efficiencies are obtained by dividing the effective fiber properties by the properties measured from a sample of heat treated fiber. These numbers are astertisked because there is currently no data available for E55 fiber heat treated to the temperatures utilized in the processing. The data presented is for E35 heat treated to 2200°C, which has a strength of 3,370 MPa (489 KSI) and a modulus of 8.89×10^{5} MPa (129 MSI). No data have been determined yet for the flexural modulus for panels fabricated from unidirectional tape, however, they are expected to be of the a value similar to the one for woven cloth.

Both strength and modulus efficiency values are quite good for CFC materials. The greater than one efficiency in modulus indicates a contribution from oriented matrix carbon surrounding the fiber. It also must be noted that these panels have fiber volume fractions of around 40%. Optimum fiber volume is thought to be around 60%, which would yield properties of around 448 MPa (65 KSI) tensile strength and 2.07×10^{5} MPa (30 MSI) tensile modulus if the same efficiencies were maintained. Fiber volume was low due to difficulties in using the equipment available for fabricating the tapes. It is expected that commercially manufactured prepreg can be fabricated with fiber volumes approaching 60%, at increased cost.

FABRICATION OF GRID HOLES

Design Requirements and Review of Conventional Drilling Techniques:

Although carbon-carbon does offer potential advantages as an ion engine grid material, such as a low coefficient of thermal expansion (CTE)[9], low grid erosion, and relatively high strength compared to other grid materials, such as graphite for example, fabricating a hole pattern into the grid blanks compatible with ion optics design requirements offers some challenges. The specified screen grid hole pattern for the carbon-carbon grids consists of 1.9 mm (0.075") diameter holes spaced 2.2 mm (0.087") apart (center-to-center hole), leaving only a webbing thickness of 0.3 mm (0.012") between the holes. The calculated open area fraction for this grid is 67%. Over the required 15 cm (6") diameter grid area, this corresponds to a total of approximately 4300 holes per grid. Requirements for the accelerator and decelerator grids are less severe since hole diameters drop to 1.5 mm (0.059") and 1.6 mm (0.063"), thus resulting in open area fractions of only 42% and 47.5%, respectively. Tolerances for hole placement and diameter were ± 0.05 mm (± 0.002").

It was found during earlier investigations,[9] however, that for hole diameters less than 2.5 mm diameter and open area fractions larger than 50% mechanical drilling of such a hole pattern is not feasible. Damage of the webbing material at the exit side of the drill was observed,[9] initiated by mechanical pressure from the drill. It was also noted that fibers were caught in the drill and pulled out of the matrix material surrounding the hole, leading to breakage of the webbing material. Boldt and Chanani[18] note that in addition to fiber pull-out and surface delamination between plies of composite materials at the exit side of the drill, similar delamination can also be observed at the entrance side of the drill. Internal delamination between plies near the holes has also been observed.[18] In addition, it was found that graphite causes extreme wear on the cutting tool and special drill materials such as diamond or tungsten carbide are required.[18] The issue of wear will be emphasized for the fabrication of ion engine grids due, the large number of holes required. Boldt and Chanani[18] point out that when drilling a 12.7 mm (0.5") thick graphite, composite at a drill speed of 0.040 mm per revolution, 2800 revolutions per minute, only 40 quality holes could be drilled with one tool. The drill was a specially designed, so called "spade drill" with a carbide tip.

Because of these problems encountered with conventional, mechanical drilling techniques, other options have been investigated. Garner and Brophy[9] reported that using electric discharge machining (EDM) excellent hole quality could be obtained. All holes on the drilling sample were of a very high, uniform quality with sharp edges and no measurable taper of the hole walls. Surface roughness features of the hole walls were estimated at ±0.01 mm or less. Unfortunately, electric discharge machining is relatively costly, Depending on the manufacturer, the price per hole range between $ 0.80 and $0.90. Given the large number of hole.s required for the grid design, a search for cheaper alternatives was conducted. Among the hole drilling techniques explored were ultrasonic grinding, laser drilling, waterjet etching and sandblasting. Results obtained with these various methods will be discussed next.

Ultrasonic Impact Grinding:

During ultrasonic impact grinding, ultrasonic vibrations arc transferred to a cutting tool. [19,20] The mechanical vibrations of the tool arc generated using a transducer operating piezoelectrically or based on magnetic induction, excited by a high frequency electronic signal ~cncrator.19 These acoustic vibrations arc then transfer-red through a metal 1001 holder (the so called "horn") to the tool.] 9 By introducing an abrasive slurry to the contact surface between cutting tool and the workpiece, the tool can grind itself into the material, producing a cut whose shape is an exact counterpart of the shape of the tool used, Vibrations of the tool typically occur at a frequency of 20 kHz with stroke amplitudes of a few hundredths of a millimeter. [19]

Ultrasonic impact grinding is therefore non-thermal, non-chemical and non-electrical process. As a result, hole qualities obtained with this technique arc excellent and rival those achieved with the EDM method. Scanning Electron Microscope (SEM) scans of ultrasonically drilled holes into a 1 mm (0.040") thick carbon-carbon sample arc shown in Figures 1 through 4. Figures 1 and 2 reveal that there is no difference between hole, characteristics at the. entrance and exit sides of the hole. Ultrasonically machine.d holes arc characterized by straight, smooth walls showing well defined, sharp edge.s. No breakage of the webbing material was observed even for an open area f ract ion of 67% anti a hole diameter of 1,9 mm (0.075"). Figure 4 also illustrates the fact that ultrasonically drilled holes have no taper. Visible on Fig. 4, however, as well as on Fig. 3 which shows a close-up of the hole wall arc short fiber segments that extend from the wall surface into the hole. The hole. shown in Figure 1 through 3 is a worst case in this regard and the number of fiber segments visible in other holes of the sample was significantly less. Fiber segment lengths can be estimated from the phonographs as < 0.1 mm. It is believed that these fiber segments will not pose a threat to proper grid operation as tbcy wiii likely be eroded completely soon after initiating thruster firing. Unfortunately, however, ultrasonic impact grinding is also a fairly expensive way of fabricating ion engine grids. As for EDM, costs for this method ranged around $0.80 per bole.

Two interesting features can further be noted on Figs 4 and 5. In Fig. 4, the fiber segm ents which arc oriented in two primary directions, at an angle of 45° with respect to each other can be seen. This is a result of the three pl ic carbon-carbon panel used in these tests (as opposed 10 the unidirectional panels discussed car] ier). Fibers arc oriented at 0^o, 45° and 90° in the three respective plies. In Figure 5, a close-up of the edge of an ultrasonically drilled hole is shown. A crack can be seen in the matrix material, exposing fiber bundles woven in the 90^o plane weave pattern used for this pane], This crack was not cause.d by the ultrasonic drilling technique, but is a remnant of the manufacturing process of the panels. During carbonization of the fiber-rc.sin matrix, the resin forms microcracks because of weight loss and densification.[21] This microcracking is the reason why "recycling" of the composite in the manufacturing process (i.e. repeated resin or pitch reimpregnation and carbonization cycles) and chemical vapor infiltration (CVI) processes using hydrocarbon gases arc necessary.[9,21]

Laser Drilling:

During laser drilling, a laser beam is focused onto the carbon-carbon sample and a hole is "burned" into the material. This interaction is a thermal process, since the material absorbs a fraction of the incident laser light, locally increasing the material temperature until material is melted, vaporized and chemically decomposed.[22] 10 order to remove the material from the cut, a gas Stream, aligned coaxial ly with the laser beam, is directed onto the drilling site. This gas stream also serves 10 protect the focusing lens for the laser from debris leaving the drill ing site and 10 remove vapor out of the laser path that might block the laser light.[22] Selection of the proper culling gas is made empirically and frequently used gases arc air, o.ygn, and helium, as well as other inert gases.[22,23] The laser used for the tests conducted in this study was a 1500 W CO_2 laser.[23] C02 lasers emit in the infrared at 1.06 x 10^4 nm. In order to produce sufficient power densities to cut composite materials, lasers have to be focused onto the material. A 1500 W CO_2 laser may be focused into a circle of 0.15 mm in diameter[22], resulting in a local power density up to 1.0 x 10]] W/m^2. Due. to the kerf, i.e. the. width of the actual cut made by the laser, tolerances arc limited 100.05 mm (0.002'')[22] and thus barely within the limits required for the ion optics design considered here.

Results obtained from the laser drilling technique arc shown in Figs 6 through 10. Figures 6 and 7 show the entrance and exit side of the laser drilled hole, respectively. As can be seen, the hole has a strong taper. The reason for this taper can be explained by the thermal interaction of the laser beam with the carbon-carbon material. Graphite fibers arc good thermal conductors.[22] As a result, heat generated by the impinging 1 aser beam is cond ucted away f rom the. drilling site laterally, causing melt down of the. material in the immediate area surrounding the. hole, leading to the "crater-like" shape of the hole as shown in Fig. 6. Figure 8 shows the wall structure of the hole. "Streaks" running the length of the hole indicate that wall material seems to have flown down into the hole during the. melting process forming the hole, The same process might have also led to the "spilling" of molten material over the edge of the exit side of the hole, as shown in Fig. 7. An extreme close-up of the hole wall is shown in Fig. 9, depicting fiber segments extending beyond the wall surface, that have been fused by the extreme heat involved in the laser drilling process. Finally, Fig. 10 shows a view of the entrance side of the hole from a direction vertical to the carbon-carbon sample. As can be seen on this figure, the hole is not perfectly round as was the case for EDM'ed or ultrasonically drilled holes.

In addition to poor hole quality, the thermal interaction of the laser beam with the carbon-carbon material also appeared to have a negative impact on the structural rigidity of the matrix material between the holes. Upon inspection of the. laser-drilled sample it was noted that the webbing material had become brittle and that the sample could be broken fairly easily. Although not fully conclusive at this point, it seems possible that due. to heat conduction along the fibers away from the holes, thermal stresses might have been introduced to the webbing material that caused delamination between matrix and fiber material or internal delamination between different plies. Finally, it was noted that the laser drilling process left a layer of soot on the webbing material surrounding the entrance side of the hole. Actual grid fabrication would most likely require a cleaning process prior to using the grids in order to improve breakdown rcsi stance.

Costs pcr hole for the laser drilling approach arc less than for EDM and ultrasonic drilling and estimates range around $0.40 pcr hole, however, results obtained with the laser drilling approach were not very encouraging in view of its application for ion grid fabrication, It should be noted, however, that there seems to exist a great difference in product quality for the laser drilling approach depending on the vendor so that results obtained in this study might have to be rc.viewed in the future.

Waterjet Etching:

During waterjet etching, a fine, high pressure, high velocity water jet is directed at the workpiece. Typical wale.r pressure.s are. 400 MPa at flow rates of 4 to 8 L/min.[24] Sometimes abrasives arc added to the waterjet to increase its cutting ability.[24] Culling is achieved by erosion and shear processes and the eroded material is then carried away from the drilling silt by the water.[24] Waterjet etching results arc shown in Figs 11 through 13. No abrasive was used in these tests[25]. Water pressures of 12 and 48 ksi were used[25] with the Photographs showing the. results of the low pressure tests. The waler jet velocity was approximately Mach 3, resulting in a cutting speed of 15 cm/min[25]. As can clearly be seen on these SEM scans, hole quality is extremely poor. The matrix material is completel y destroyed in the, immed iate area surrounding the hole.

These. e ffects arc typical for a waterjet etching. Korican[24] note.s that delamination of composites is noted primarily at locations surrounding initial penetration of the workpiece by the waterjet. The problem is commonly circumvented by placing the location of initial penetration away from the desired cut of the workpiece and then guiding the jet towards the cut.[24] In the case of drilling small diameter holes as required for grid fabrication this technique is not applicable. Every hole drilled represents a location of initial penetration, leading to the. kind of destruction of the matrix material as shown in Figs 11 through 13. Figure 13 atso reveals that hole shapes arc not nearly as circular as those obtained with the EDM and ultrasonic drilling method.

Because of the extraordinary poor hole quality, waterjet etching was not considered as a serious alternative for the Fabrication of carbon-carbon composite grids, and, thus, no cost estimates were obtained for this method.

Sandblasting:

Preliminary attempts were made to investigate. the technique of sandblasting for the fabrication of car-bon-carbon grids. During sandblasting, sand particles of a specified grit size arc being introduced to a high velocity, compressed air stream and ejected through a nozzle[26]. In this sense, sandblasting is a method very similar to abrasive waterjet etching were the carrier medium water has been replaced by air. The sand/air mixture then impinges on the workpiece and the high velocity, sharp edged sand particles erode and shear the workpiece material, which is subsequently carried away in the air stream. Although initial estimates indicated that this method is very cost ef fect ive (esti mated at roughly $0.20 pcr hole), hole quality is poor. Even inspection of the holes with the bare cyc revealed a significant taper 10 the holes. Increasing air pressure, and, thus, speed and moving the nozzle closer to the workpiece might have resulted in a reduced taper.26 However, the only manufacturer specialized in sandblasting holes of the size required for ion engine grids that could be located did not have equipment large enough to facilitate the fabrication of an entire, 15 cm grid.[26] Therefore this method was not investigated any further.

CONCLUSIONS AND RECOMMENDATIONS:

Flat plates for ion optics were fabricated from carbon-carbon composites using a pitch-based fiber with a high tensile modulus in the plane of the optics. Panels were fabricated from laminated plies of unidirectional tape oriented to reduce the number of fibers which will be cut when the ion extraction holes arc machined. The plates were flat to within ± 0.05 mm over an area of diameter 1 S cm. Tests indicate that the panels have a negative CTE up to approximately 900 K; above this temperature the CTE is expected to have a positive value. that increases slowly with increasing temperature.

Since conventional, mechanical drilling techniques arc not suitable for the fabrication of carbon-carbon ion engine grids duc to breakage, of the workpiece, an investigation of more advanced drilling techniques was undertaken. EDM, ultrasonic impact grinding, laser drilling, waterjet etching and sandblasting methods have been studied. only the EDM and ultrasonic drilling approach appear feasible for the machining of carbon-carbon grids. Both techniques have costs ranging from roughly $0.70 to $0.90 pcr hole. Cheaper drilling techniques could be identified, however, only at the expense of significantly lower hotc quality.

An approach utilizing the high quality provided by the EDM and ultrasonic techniques, yet avoiding their high costs, was recently suggested by onc of the authors.[27] The EDM and the, ultrasonic grinding technique can produce almost any hole shape by shaping the electrode or cutting tool accordingly. Rectangular shaped holes could provide the, same open area fraction as circular holes while, requiring fewer holes pcr grid and allowing for larger webbing thicknesses.[27] Since, costs pcr hole essentially remain unchanged, a cost reduction of nearly 75% could be obtained 10 EDM a 1 S-cm grid using rectangular holes versus grids using circular hole patterns.[28] A photograph of a (trilling sample into carbon carbon using 1.9mm x 6.35 mm (0.075" x 0.250") holes is shown in Fig.14. This hole geometry would require only 1100 holes to provide the same open area fraction of 67% for the 15 cm screen grid as the pattern consisting of 4300, 1.9 mm (0.075") diameter circular holes. Webbing thickness in the case shown in Fig. 14 is 0.56 mm (0.022") at its narrowest location. If smaller webbing thicknesses can be tolerated then open area fractions could be increased further and performance of the ion thruster improved. One issue of concern is the variation of plasma properties across the hole length which might have a negative impact on beamlet characteristics. Research efforts arc necessary to full y evaluate the Usefulness and feasibilit y of using rectangular hole patterns for carbo-carbon grids. Recent successes in mechanical machining of thin, dished graphite grids may also be applied to the fabrication of carbon-carbon panels and possibly reduce the cost of machining the ion extraction apertures.

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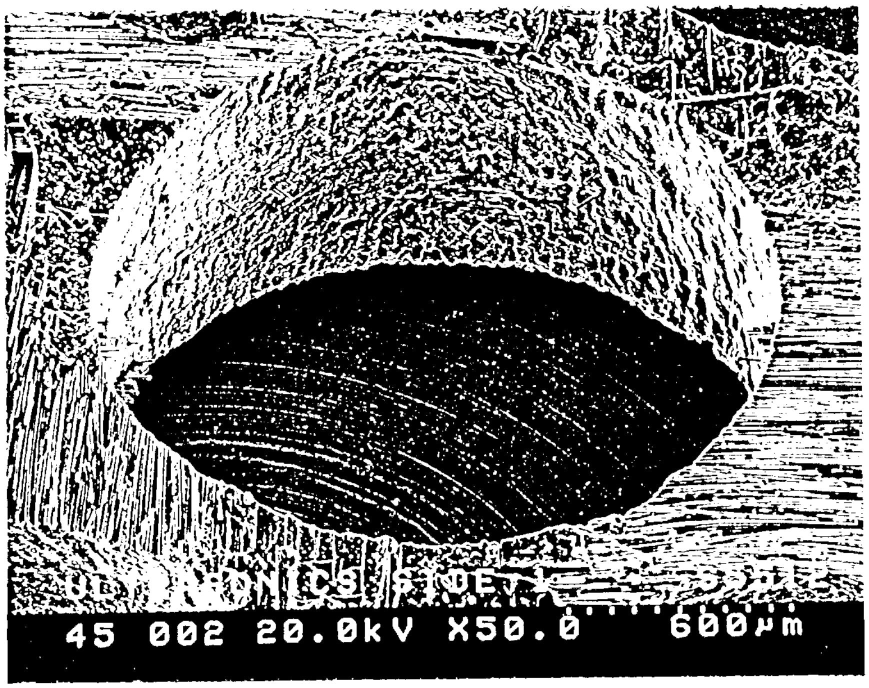


Figure 1

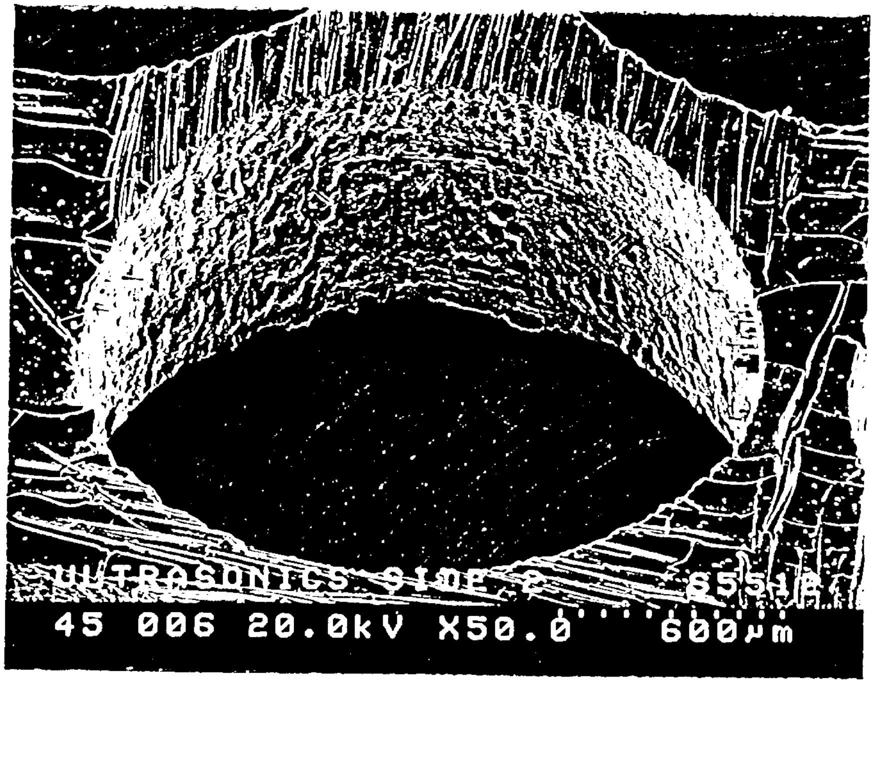


Figure 2

Figure 3

Figure 4

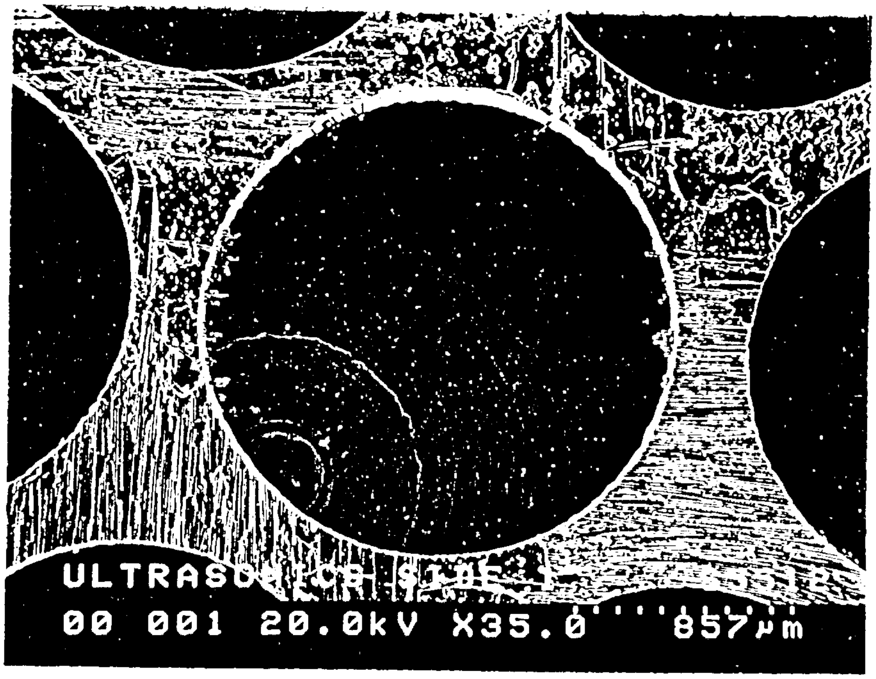
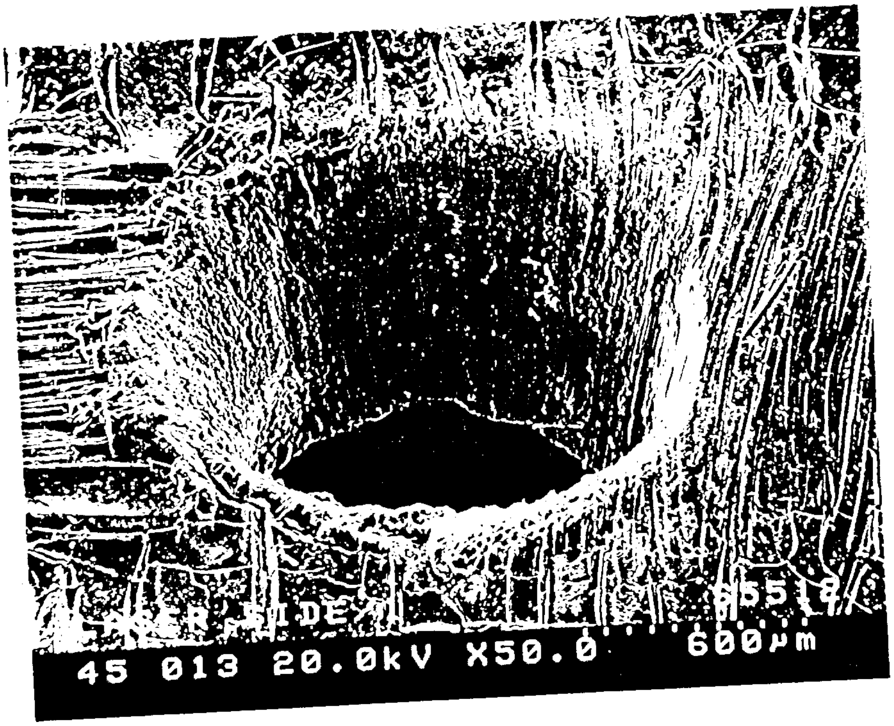


Figure 5

Figure 6



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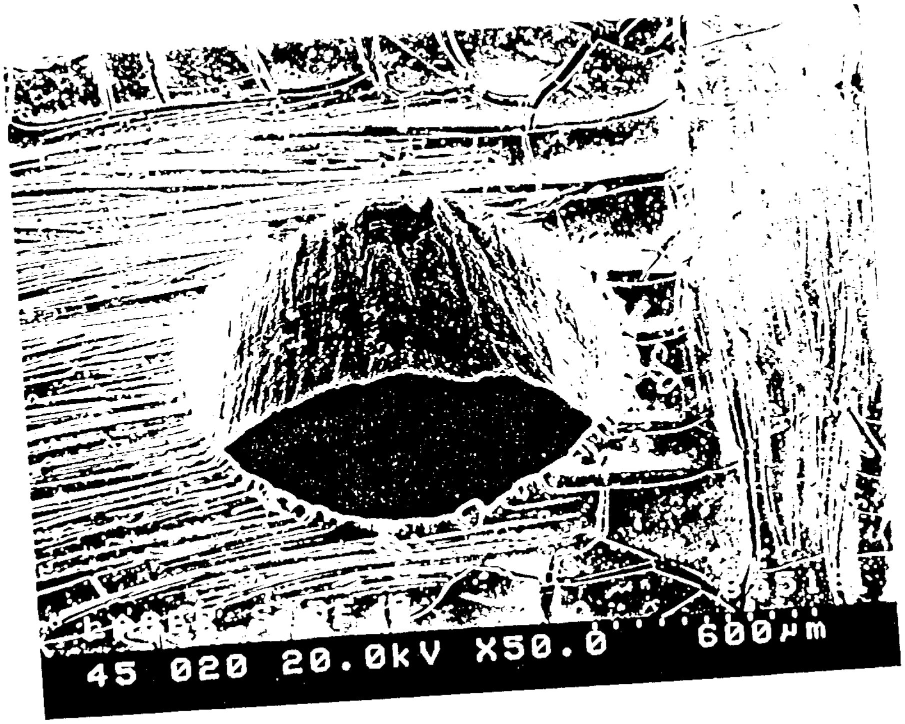


Figure 8

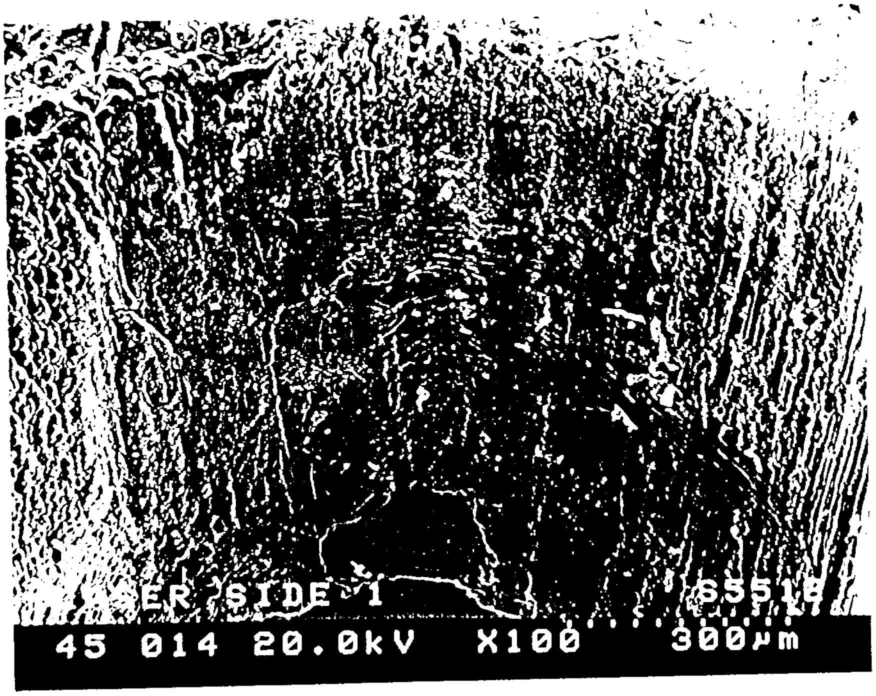


Figure 9

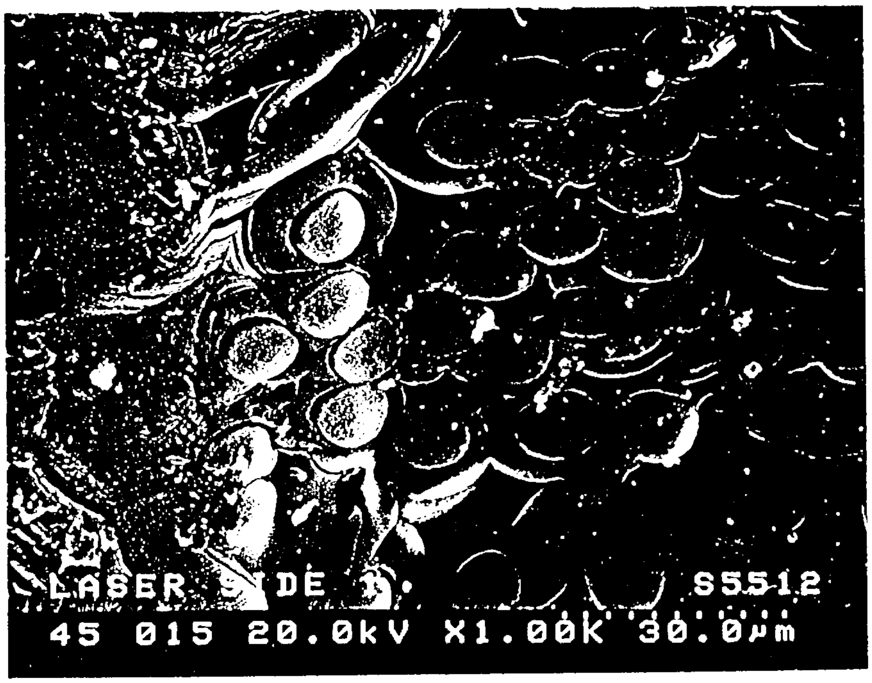


Figure 10

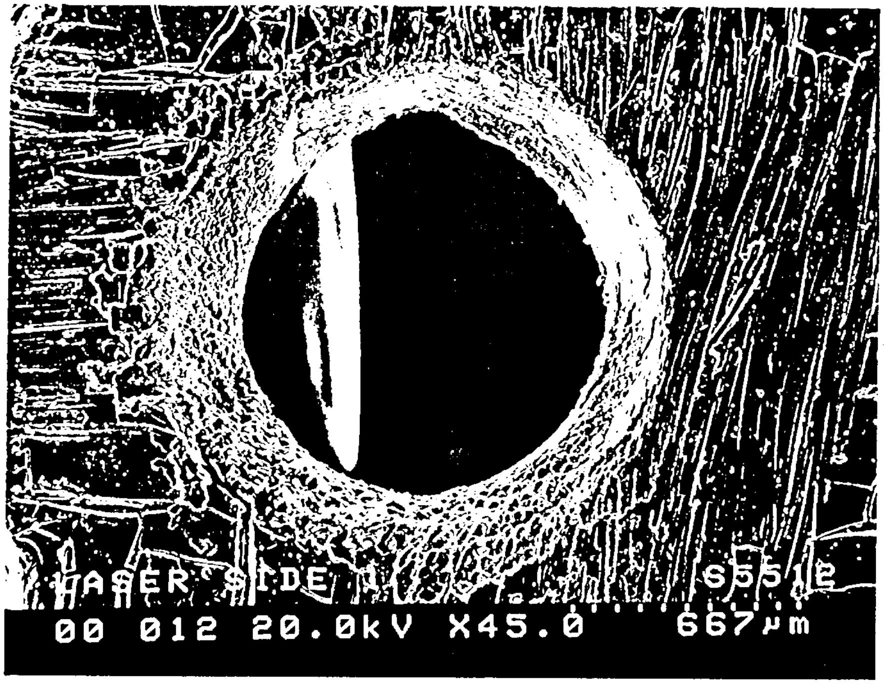


Figure 11

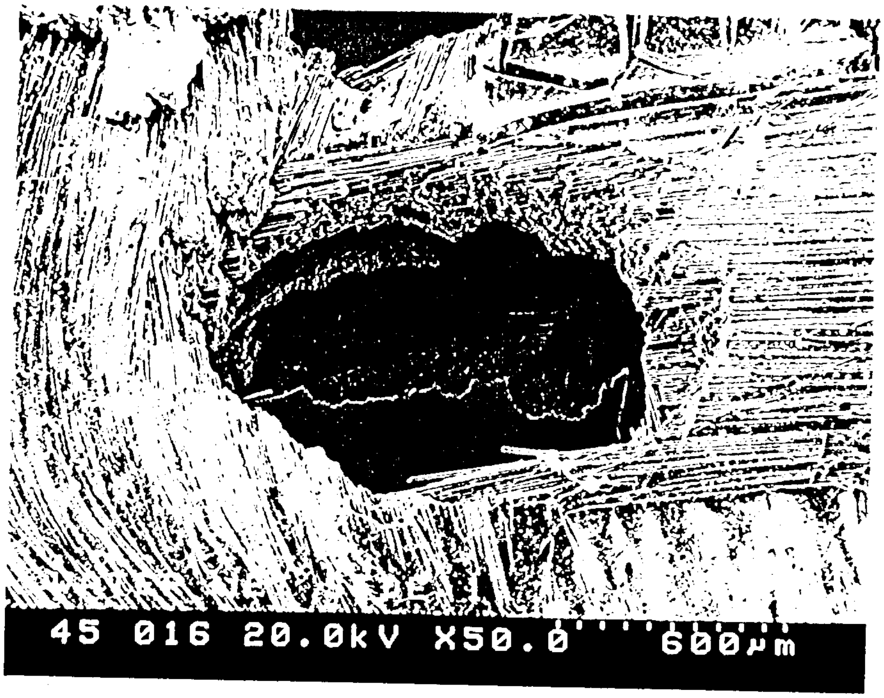


Figure 12

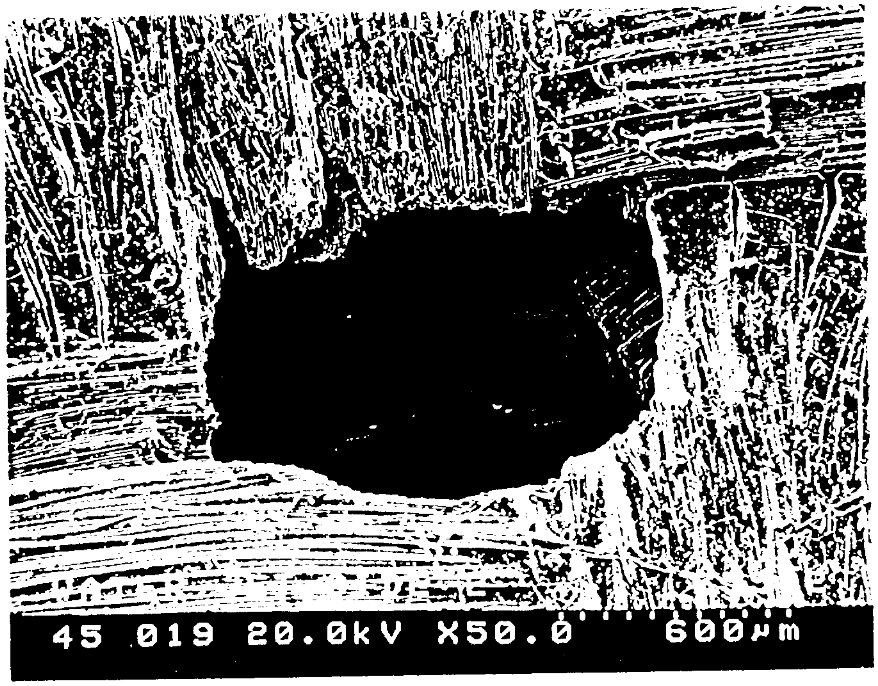
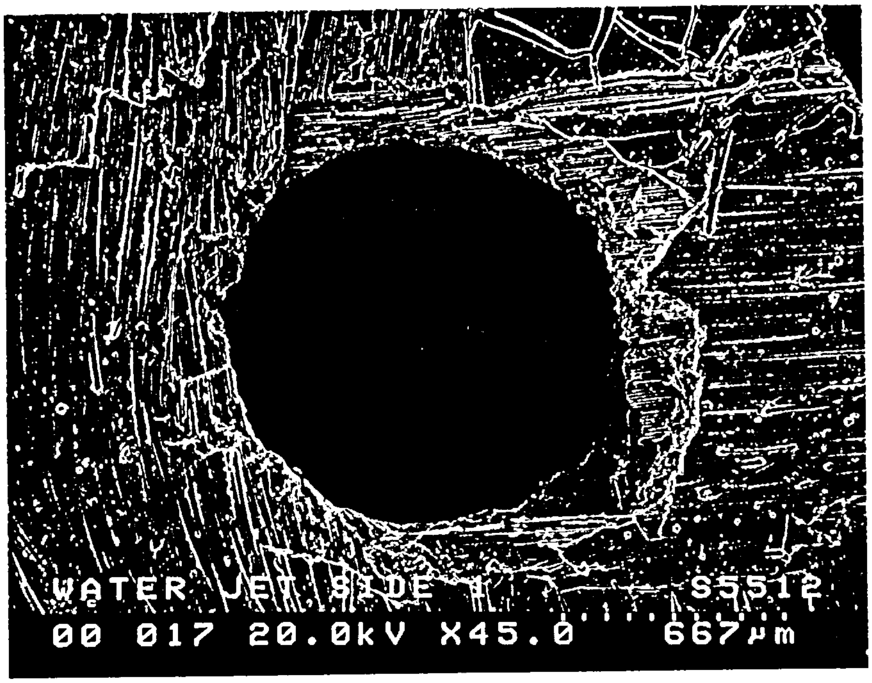


Figure 13



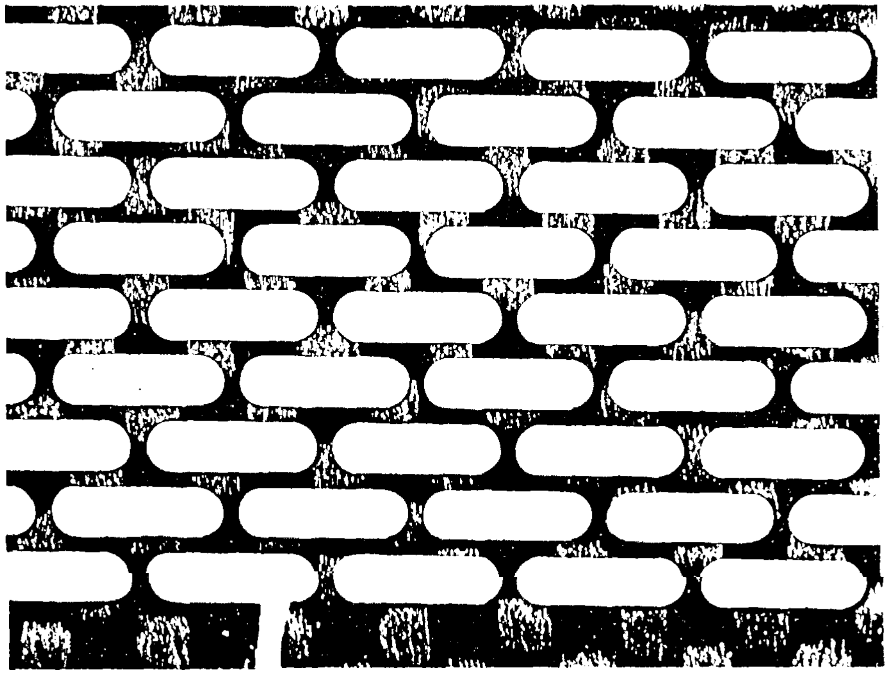


Figure 14