INVESTIGATION OF DRILLING INDUCED DAMAGE IN PPS/GLASS FIBER REINFORCED COMPOSITES

By

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COMPOSITES

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CHAPTER 1

INTRODUCTION

Composite materials, because of their superior strength-to-weight and stiffness-to-weight ratios, are being used increasingly in high performance applications. While much work has been done in studies of mechanical behavior and mechanics of composites, less has been done in the area of manufacturing processes, particularly in machining, (1). The use of composite materials in aerospace and aeronautical structures has resulted typically in improved structural performance, but the fabrication cost is higher, as compared to conventional metallic structures (2). Hence, increased emphasis is now being placed on machining composites more accurately and efficiently.

Background

Several nontraditional machining processes, such as laser beam machining, water jet machining, ultrasonic machining and electro-discharge machining, have been developed to machine the so-called hard-to-machine materials, including composite materials. Nevertheless, conventional machining processes such as drilling, routing, sawing, milling and countersinking, continue to be used widely (3). In the aerospace industry, drilling of composites is the most common operation. A number of problems are encountered while drilling composite laminates, including delamination, fiber breakout, and fraying. These defects are unique to fiber composites and are not seen in homogeneous materials.

Delamination during drilling is the most important problem that needs to be tackled. Delamination is generally regarded as a resin or matrix dominated failure behavior, which usually occurs in the interply region. It appears as peeling away of the bottom ply or plies and is attributed to the force of the drill which pushes the layers apart before cutting through them. Figure 1 is a good representation of delamination during drilling. Note that the delamination at exit is more than that at entry. Delamination can often be the limiting factor in the use of composite materials for structural applications, particularly when they are subjected to compressive, shear or cyclic loads. (3)

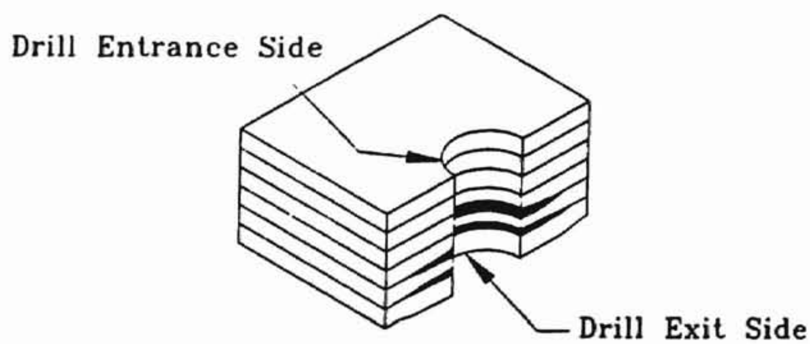

Figure 1 : Drilling induced delamination in Composites (4)

There is a whole gamut of light weight high-strength composites used in the industry today. Probably the greatest potential for lightweight high-strength composites exists in inorganic-fiber-organic-matrix composites. Although the choice of materials for the two constituents making up such fiber composites is wide, no combination of inorganic fiber and organic matrix has yet proved as successful as the glass-fiber-reinforced plastic composite (5). Studies in this research deal with a thermoplastic matrix, Polyphenylene sulfide (PPS) with E-glass fibers as the reinforcing material.

Thermoplastic resins, sometimes called engineering plastics, include some polyesters, polyether imide, polyamide imide, polyphenylene sulfide, polyether ether ketone (PEEK), and liquid crystal polymers. They consist of large, discrete molecules which melt to a viscous liquid at the processing temperature, typically 500° to 700°F (260° to 371°C), and, after forming, are cooled to an amorphous, semicrystalline, or crystalline solid. The degree of crystallinity has a strong effect on the final matrix properties. Unlike the curing process of thermosetting resins, the processing of thermoplastics is reversible, and by simply reheating to the process temperature, the resin can be formed into another shape if desired. Thermoplastics, while generally inferior to thermosets in high temperature strength and chemical stability, are more resistant to cracking and impact damage. However, it should be noted that recently developed high performance thermoplastics such as PPS, PEEK, have a semicrystalline microstructure, and hence exhibit excellent high-temperature strength and solvent resistance.(5)

Thermoplastics offer great promise for the future from the manufacturing point of view, since it is easier and faster to heat and cool a material than it is to cure it, as with a thermosetting matrix such as epoxy. This makes thermoplastic matrixes attractive to high-volume industries, such as the automotive industry. Currently, thermoplastics are used primarily with discontinuous fiber reinforcements, such as chopped glass or carbon/graphite. However, there is great potential for high performance thermoplastics reinforced with continuous fibers. For example, thermoplastics could be used in place of epoxies in the composite structure of the next generation of fighter aircraft. (5)

In the aircraft industry, sheets of composites are joined using rivets. With nearly one million rivets used in a single aircraft, drilling is a very important operation and many studies have been done on minimizing the damage from drilling. It is very difficult to analyze the damage caused during drilling, due to the complexity in the structure of the composites. Delamination, fiber breakout, fraying etc., have a cumulative effect on the hole quality, delamination being the most dominant among them. Delamination is generally worse on the back side, or the drill exit side, of the material, and the damage often extends many layers into the laminate. One of the most serious problems, in the failure of composites, is the propagation of these inter laminar cracks. X- radiography, optical and ultrasonic techniques have been used to observe damage, however it is difficult to quantify it since it is not uniform. An alternative would be to perform mechanical tests on these materials to observe any effect on the strength or fatigue life of the material due to damage. Drilling feed rate, speed and tool geometry, all effect the amount of damage done during drilling. The use of backing pressure during drilling has been known to reduce damage, however, it is difficult to apply backing pressure in some cases (6).

In this study test have been performed on PPS/glass fiber composites. The semicrystalline engineering thermoplastic, polyphenylene sulfide, is an excellent matrix for high performance fiber reinforced composites. When reinforced with glass fibers it shows excellent inter laminar fracture toughness typical of high performance thermoplastic composites. The nominal properties of PPS are shown in Table 1 (7)

Objectives of the Study

The primary objective of this study is to investigate the damage introduced into PPS/glass fiber composites during drilling and its effect on the strength and fatigue life of the composite. A vertical milling machine was used to drill the holes. This machine is capable of giving three feed rates of 0.0015, 0.003, 0.006 ipr. During the conceptual stage of the research it was estimated that a wide range of feed rate should be used. The fact that we could get only three variable feed rates was a disadvantage that could not be overcome. It would have been useful if we could get atleast a 20 fold increase in the feed rate from the lowest to the highest as against just 4 fold in our case. The drilling speed, however, was kept constant at 2000 rpm. Holes were drilled with and without backing plate. Numerous tensile and fatigue tests were performed at different strain rates and load levels. All these tests were performed on a MTS machine. Study was also done to explore ways in which we could repair the damage done after drilling. Resin injection technique gave promising results when used to repair impact induced damages (8). The process involves injecting a epoxy or other high strength adhesive into the damaged region. The pressure required can be obtained by using a syringe. The adhesive helps to reduce the stress concentration caused due to matrix loss and effectively increases the fatigue life. This technique was tried to repair the damage induced during drilling.

CHAPTER 2

REVIEW OF THE LITERATURE

The damage of composites due to drilling has been studied since about 1975. Much of the previous research has concentrated on evaluating the extent of delamination occurring during drilling and its effect on the tensile strength of the composite laminate (5). X-radiography techniques have been used to monitor the initiation and accumulation of damage in composite laminates (2). Ho-cheng and Dharan (1) studied the phenomenon of delamination damage produced during the drilling of graphite/epoxy composite laminates. A model was proposed that relates the delamination of the laminate to drilling parameters and composite material properties. Possible mechanisms responsible for delamination during drilling and the analytical model to predict the onset of delamination were discussed.

Andrews et. al.(6) conducted tests to evaluate the influence of drilling-induced defects in bolted joints under static and fatigue loads. Testing was performed in a bearing tension frame which loaded the coupon under 70% tension and 30% pin load. Pin movement was found to vary with respect to the delamination diameter, specimen thickness, and stacking sequence. Massarweh and Hough Jr. (9) performed tests to determine if the hole quality is a viable tool selection criterion in the initial stages of process planning. They found that bit design and feed rate were the most significant factors in determining hole quality. They concluded that the interactions of drill design with both feed and speed were significant and should be considered when constructing response models. Jain and Yang (3) present an analytical model to predict critical thrust force and critical feed rate at which the delamination crack begins to propagate. Since thrust force, generated during drilling, is a function of feedrate and tool geometry, they suggest solutions such as variable feed rate and drills with a small chisel edge to avoid delamination. They performed tensile tests on a unidirectional T300/5208 Graphite-Epoxy composite and found that the results agreed with the proposed model. They identified chisel edge as a major contribution to the thrust force, with point angle being only of secondary importance. Ho-cheng, et. al (10) studied the chip characteristics, specific cutting energy, drilling force, hole surface roughness and edge damage on representative thermoset-based and thermoplastic-based composites, with heavy and light fiber loading ratios. The observations revealed a common fracture mechanism in chip formation as well as the sensitivity to material defects in bulk volume, due to the content of hard fibers.

In order to optimize the use of fiber-reinforced composite materials in primary aircraft structures and other demanding applications, the damage tolerance of such materials under both static and fatigue loading must be established. The most common failure mechanism in laminated composites is delamination (2). Pengra and Wood (11) were the forerunners in the study of influence of hole quality on the fatigue behavior of composite materials. In as early as 1980, they performed numerous static and fatigue tests on Narmco 5208/T300 graphite/epoxy composite laminates. Their results showed that a hole chip out defect reduces the static and cyclic endurance characteristics. The over sized holes also lowered the cyclic pin bearing endurance, but this defect did not effect the cyclic pin bearing characteristics. Delamination of the exit face ply during hole fabrication did not influence static tension pin bearing strength and the effect of this flaw on pin bearing endurance was not significant. They proposed a relaxation of delamination requirements for holes fabricated in graphite/epoxy composites, with additional supporting data.

Andrews et. al. (4) performed tension bearing by-pass tests on coupons under ambient and elevated temperature wet conditions. Specimens were tested in a bearing tension frame to static failure in order to measure the failure loads and to calculate the pin bearing stress. From static test results, the fatigue load was selected as 66% of the static pin bearing failure load. Coupons were then tested under pin bearing fatigue loading at ambient and elevated temperature wet conditions. Experimental results showed the pin movement to vary with respect to delamination diameter, specimen thickness, and configuration. Results give an indication of the effects of environment and hole quality under pin bearing load. Large variations in the drilling-induced damage tended to cause variations in the pin bearing response of like specimens.

Butler, et. al. (12) performed fatigue tests on rail shear specimens and found that the fatigue lives obtainable are very dependent upon the surface quality of the exposed edge. Polishing the edge resulted in a significant increase in fatigue life. This is presumably due to removal of potential cracks. Curtis (13), found that even if small slots were introduced into the coupon ends, the lives of the specimen increased drastically. This was probably because the failure zone was shifted from the coupon edge, where constraint and edge effects lead to complex stress fields, to a region where a simple shear stress field exists. He also noted that the effects of shear fatigue loading on composite materials are quite significant; in the case of glass fiber/ epoxy the stress at long life times was reduced to nearly 50% of the static strength (13).

Prior to this study, Nayak (14) and Powers (15) conducted tests on similar PPS/glass fiber composites. Nayak studied the open-hole tensile strength and the fatigue behavior of a 8H-satin weave glass fiber reinforced PPS. The effect of hole quality, hole size and elevated wet condition on the strength and fatigue life were studied. The results of his tests indicated that boiling water did not have any effect on the strength of the composite system. Thus the material did not have any moisture absorption problem. In fatigue, the life to fracture decreased when a 6.4 mm hole was introduced into the laminate. The weave of the glass fiber thus effected the strength of the laminate. Hole finish did not seem to have any effect on the static or fatigue life of the composite system studied. Powers studied the initiation of damage due to a drilled hole. He also tried to determine if the material had a fatigue limit. He concluded that the PPS/E-glass composite did seem to have a fatigue limit. The material did not damage linearly. It had some early damage, then reaches a plateau region where there is some progressive damage, then there is continuous damage to failure.

Liu et. al. (8) discussed the reparability of impact induced damage in an SMC composite which is made of chopped glass and polyester matrix. They attempted to repair an impact induced damage by using 1) a resin injection technique 2) a reinforcing patch. The first technique was used to eliminate the delamination that had occurred due to the impact. Resin injection was employed to reduce the stress concentration caused by geometric discontinuity. The resin was intended to fill in the voids and the delaminated region of the damage. The experiments proved conclusively that the resin injection technique was a very efficient technique for repairing composites with impact-induced damage.

CHAPTER 3

EXPERIMENTAL PROCEDURE

Material

The material used for all the tests was LG31-60 manufactured by Avtel, a division of Phillips petroleum company, located in Bartlesville, Oklahoma. As mentioned in the introduction, it is a glass fiber reinforced thermoplastic composite. The specification of this composite is as follows.

<u>LG31-60</u>

L → Tougher version of PPS, semi crystalline.

G → Glass reinforcement, (E-glass).

31 → Fabric style, 7781 8-Harness satin weave.

60 → 60% fiber, weight percent.

The laminate was made by laying up nine plies to get an overall thickness of 2.58 mm (≈ 0.1015 inches). The lay up of the plies is given below.

Top	8	7	6	5	4	3	2	1
+45°	0°	0°	+45°	0°	+45°	0°	0°	+45°

The profiles of the coupons used in fatigue can be varied to ensure failure away from the stress concentrations at the gripped portions of the specimen. Waisting of the specimen usually ensures static failures away from the grips, but not necessarily in fatigue. This is because waisting normally disturbs the lay-up. The fibers which are cut transfer the fatigue loads to the grips and trigger failure within the grips at short life times. In this research, stress concentrations around the hole are introduced, ensuring the failure of the coupon at the hole. Hence, the specimens used for all the tests were in the shape of a rectangular plate with a hole.

Property	Value
Density, gm./cc.	1.36
Tensile strength, MPa	78
Elongation, %	4
Flexural strength, MPa	147
Flexural modules, GPa	3.4
Izod impact, ft.-lb./in.	
Notched	0.4
Unnotched	8.0

Table 1 : Nominal properties of polyphenylene sulfide (PPS) (7)

Property	Value
Density, gm./cc.	2.6
Young's Modulus GPa	72.3
Elongation, %	4.8
Tensile Strength Mpa	3447
Fiber Diameter μ	13.5

Table 2 : Nominal properties of Continuous Reinforcing E- Glass Fibers. (7)

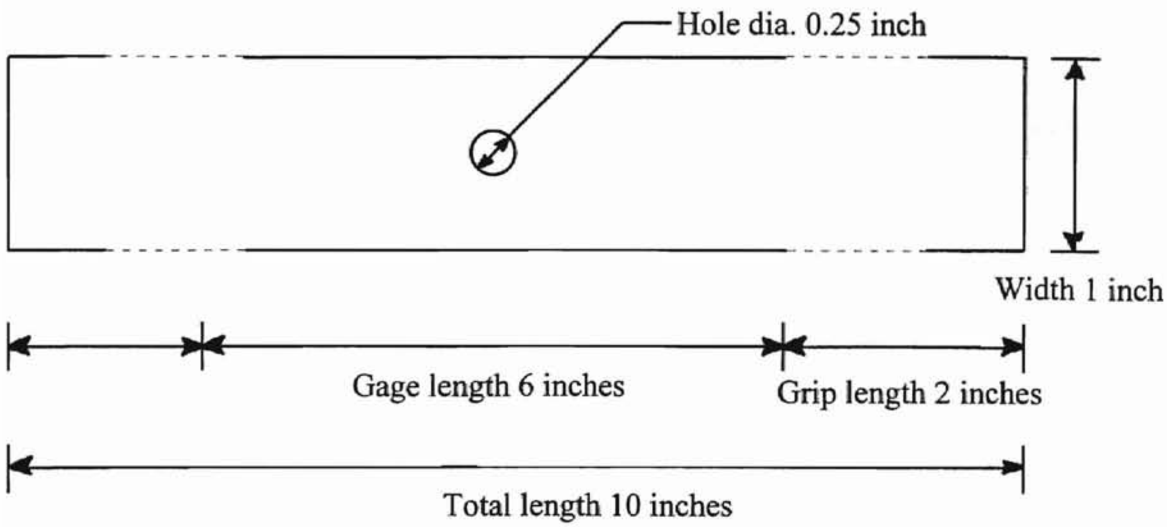

Figure 2 : Geometry and dimensions of the specimen used.

Specimen preparation

The specimens were cut using a band saw along the direction of orientation of the main or wrap fibers, which in this case was 0°. The reasoning behind this is that, for the orientation of the fibers to be specially orthotropic (according to the ASTM D-3039/D 3039 M -93), it was necessary to cut it either along 0° or 45°. Since it was easier to cut along the 0° than along the 45° it was decided to cut along the 0°. The roughly cut specimens were then trimmed using a milling machine at a low speed to get the final dimensions. A jig was used to hold the specimen so that it was not damaged while machining. Holes were drilled at the center of the specimen using a HSS drill of 0.25 inch diameter. The drill speed was maintained at 2000 rpm and kerosene was used as the coolant. Three feed rates were used to drill the holes viz. 0.0015 ipr, 0.003 ipr and 0.006 ipr. Sets of specimen were made with holes drilled with and without a backing plate. The backing plate used here was a half inch thick ply wood sheet. The specimen was clamped to the block so that the entire specimen was supported by the sheet. Use of a backing plate results in a decrease in the extent of damage, since the lower layers of the laminate get additional support from the plate. The guidelines for the dimensions of the specimen were taken from ASTM standard D 3039/ D 3039M - 93, which is the " Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials ". The dimensions of the specimen used, are shown in Figure 2. It was found that there was no noticeable slipping from the grips during the test, without the use of end tabs, hence end tabs were not used for any of the tests.

Test Methods

Since axial fatigue testing gives more data and information than flexural fatigue testing, it was decided to perform axial fatigue testing on the coupon. The tensile and axial fatigue testing were performed on a MTS machine (load frame - series 312) having a load capacity of 22,675 kg (50,000 lb.). The specimens were held using steel wedge friction grips attached to the MTS. For all the tests visual alignment was used to ascertain that the specimens are aligned. All the tests were carried out at room temperature. Tensile tests were carried out at different strain rates in order to document its effect on the strength of the material. For fatigue tests, sinusoidal loading under tension was used at a frequency of 10 Hz. The control mode for the test was strain control, where a constant displacement was the control factor. This method of testing generally exhibits longer fatigue lives than load or energy control methods. The magnitude of the applied stress decreases as the laminate is damaged. The strain energy also decreases as the test proceeds. The viscoelastic behavior of the matrix results in generation of heat during cyclic loading. In order to avoid this researchers recommend keeping the cyclic frequency below 30 Hz (16). In the present case, too, no temperature rise was detected. As mentioned earlier, ASTM D 3039/3039M -93 was used as the standard for the tensile tests, and ASTM D 3479 -76 (Reapproved 1990) was followed for the fatigue tests. The MTS was checked for calibration before the tests were conducted.

For the fatigue tests the MTS was adjusted to shut off as soon as the specimen failed to be able to note the number of cycles to failure. The fatigue ratio, R, was kept at 0.1.

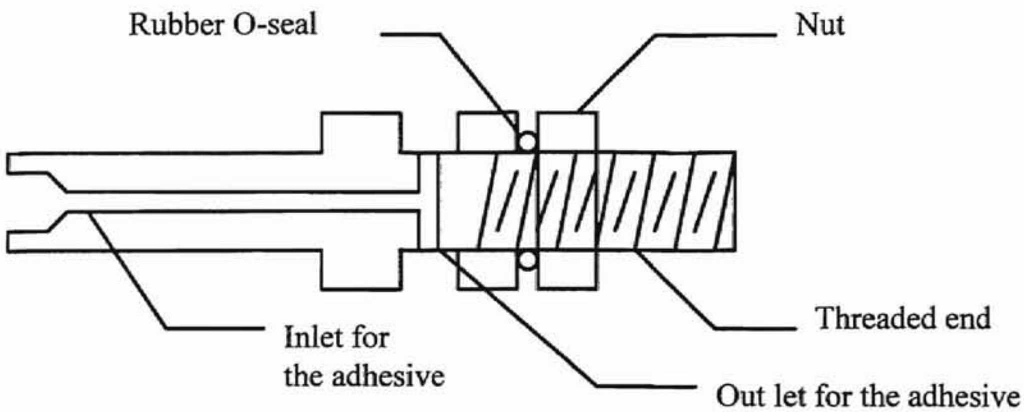

Figure 3 : Fixture to inject the adhesive into the damaged areas around the hole.

A few fatigue tests were performed on the resin injected samples. The fixture used to inject the resin is shown in Figure 3. The fixture was so designed that the adhesive will flow uniformly all around the hole. Two resins were used in this research. 1) Ecobond 45 LV + hardener in 1:1 ratio, manufactured by Grace specialty polymers. 2) Epolite 2315 + hardener in 1:3 ratio, manufactured by Hexcel. Both these adhesives were cured at room temperature, curing time being 24 hours. These two were chosen because, apart from their high strength, they are compatible to both glass fiber and PPS. Resin was injected using a syringe in an attempt to squeeze it into the damaged areas round the hole.

Most of the work involved the comparative study of results obtained from tests done on specimens drilled with different feed rates and drilling conditions. A zoom microscope was used to observe and photograph the fractured specimens. Photographs were also taken of the holes drilled under different conditions to observe any macroscopic differences between them. Thin sections near the fractured surface were cut using a low speed diamond saw. The cutting speed and the load acting on the wheel were varied in order to minimize the distortion of the cut surface. Most of the sections were cut at a very low speed and load so that the delaminated regions do not get covered with the sheared matrix. It took 15 to 20 minutes to cut through the cross section of the specimen. However, despite all precautions, the zoom microscope could not detect any delamination or other damage present on the surface. Hence, the Scanning Electron Microscope (SEM) was used to get a more explicit view of the damaged areas around the drilled hole, and the fractured surfaces.

CHAPTER 4

RESULTS

Tensile tests were first done to evaluate the strength of the material. Tests were performed on specimens that had holes drilled with the three feed rates used throughout the research viz. 0.0015,0.003,0.006 ipr. Carlsson (17) suggested that, for polymer matrix composites, the cross head rate should be 0.5 -1mm/min. Using this guide line the first set of tensile tests were performed at a strain rate of 0.0127mm/sec. A preload of 0.3 KN. was applied to avoid any slipping of the specimen during the test. The results are shown in Table 3.

Specimen no.	Drilling feed rate ipr	Maximum Load KN.	Maximum Stress MPa
1	0.0015	6.62	136
4	0.003	6.25	127
3	0.006	6.16	125
2	0.006	6.42	131

Table 3: Tensile Strengths of specimen drilled with different feed rates at a cross head rate of 0.0127 mm/sec or a strain rate of 8.3×10^{-5} mm/mm.sec.

It was observed that the strength was much less than that observed by Nayak (14) and Powers (15). On comparing the operating parameters with those of Nayak and Powers it was found that both had used a much higher strain rate. Hence, another set of tests, was performed at a higher strain rate of 0.154 mm/sec. Strengths as high as 238 MPa was observed, for these high strain rate tests. The results are shown in Table 4. These results were in accordance to what Nayak (14) and Powers (15) had obtained.

Specimen no.	Drilling feed rate ipr	Maximum Load KN.	Maximum Stress MPa
30	0.0015	8.4	177
5	0.003	11.7	238
29	0.006	9.4	192

Table 4: Tensile Strengths of specimen drilled with different feed rates at a cross head rate of 0.1524 mm/sec or a strain rate of 0.001 mm/mm.sec.

Some tensile tests were performed at an intermediate cross head rate of 0.084 mm/sec in order to be able to predict a general trend on the effect of strain rate on the tensile strength of the specimen. The results are in Table 5. It was observed that strain rate has a significant effect on the strength of the specimen. The relationship between strain rate and strength is shown in Figure 4.

Specimen no.	Drilling feed rate ipr	Maximum Load KN.	Maximum Stress MPa
32	0.0015	8.8	179
38	0.003	8.9	181
33	0.006	8.9	181

Table 5: Tensile Strengths of specimen drilled with different feed rates at a cross head rate of 0.08467 mm/sec or a strain rate of 5.5×10^{-4} mm/mm.sec.

Having determined the strength of the material, tension-tension axial fatigue tests were performed at a frequency of 10 Hz. At this frequency, the specimen is undergoing very high strain rates. Since it was not practical to perform tensile tests at these high strain rates, it was decided that the strength obtained from the highest strain rate would be used as the strength of the specimen. The maximum stress was varied between 50 to 30 % of this tensile strength. The first set of fatigue tests were performed at a maximum load of 5 KN. and a minimum load of 0.4 KN. It was observed that as the test progressed the stress level decreased. Table 6 shows the change in stress level throughout the life of a specimen. Figure 5 shows this change in load level with time, graphically.

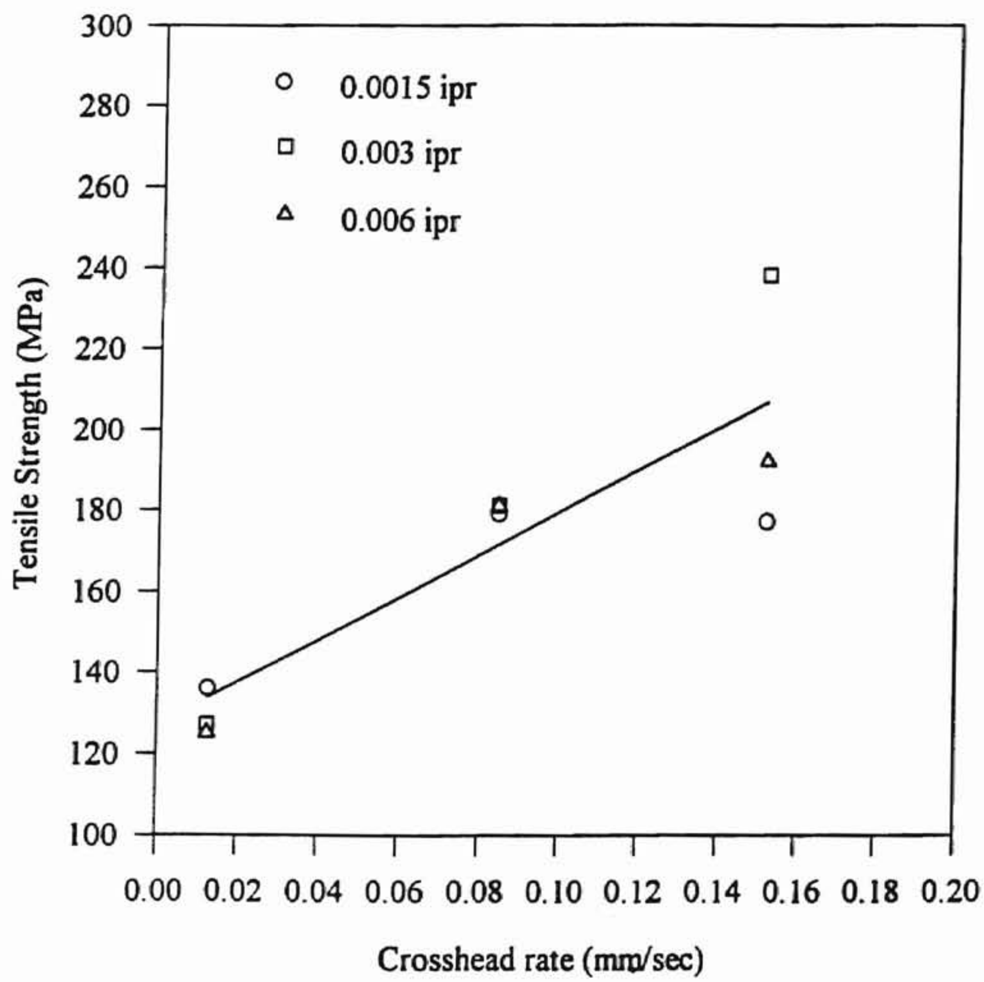

Figure 4 : Effect of cross head rate on the tensile strength of PPS/Glass fiber Composite.

Cycles N	Maximum Load KN.	Minimum Load KN.
0	5	0.5
1800	4.8	0.5
3000	4.6	0.3
9600	4.6	0.3
19800	4.5	0.2
22580	4.4	0.1

Table 6: Change in load level as the fatigue test progressed for a specimen initially loaded at 5 KN. max and 0.5 KN. min. Hole was drilled with a backing plate. The specimen no. 23 failed at 23580 cycles.

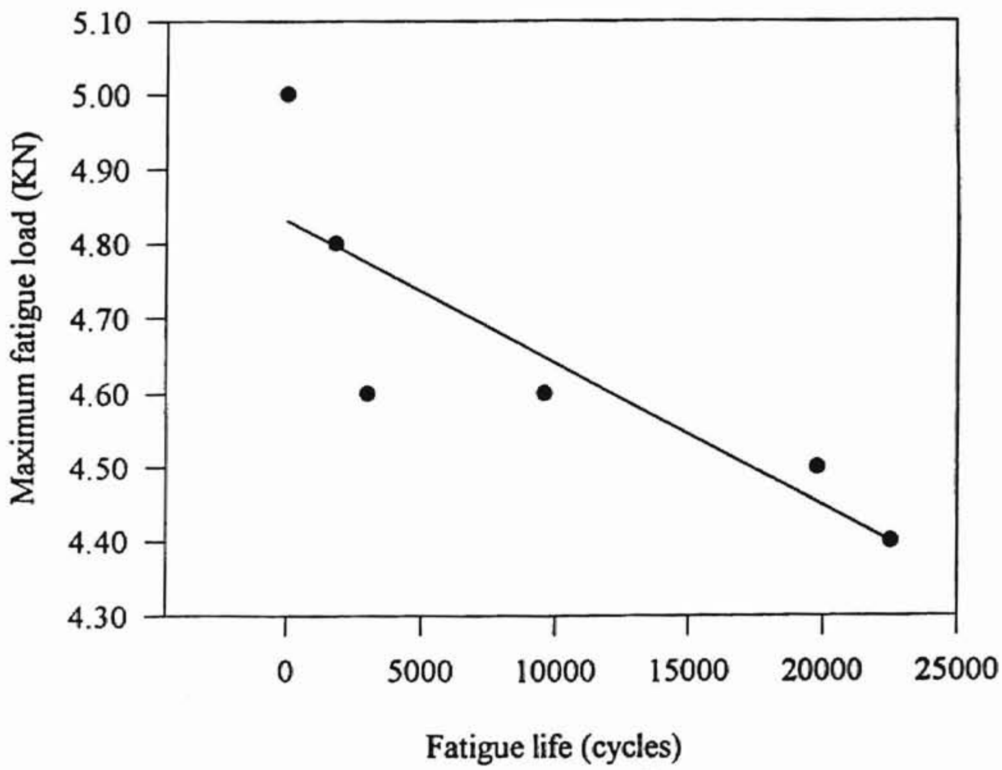

Figure 5 : An illustration of the falling stress level as a constant displacement fatigue test proceeds.

The decrease in the maximum stress was due to the damage induced in the specimen as the test progressed. Hence, if the minimum load was kept zero, there would be a compressive stress developed in the specimen. The fatigue life of most laminate composites are drastically reduced if they are exposed to compressive stresses. In order to prevent, this it was decided to keep a minimum load of 0.4 KN. No compressive load was observed for any of the tests that were performed throughout this research.

The change in stress level was also monitored for the fatigue tests that were performed at other stress levels. As Table 7 shows when the maximum stress was 70 MPa, the stress tended to increase with time, where as from Table 8, for maximum stress of 82 MPa, the stress decreased initially, and then decreased. Possible explanation for this behavior are discussed in the next chapter.

Cycles N	Maximum Load KN.	Minimum Load KN.
0	3.4	0.4
61800	3.6	0.6
92400	3.7	0.8
130200	3.9	0.9
228640	3.5	0.5

Table 7: Change in load level as the fatigue test progressed for a specimen initially loaded at 3.4 KN. max and 0.4 KN. min. Hole was drilled with a backing plate. Specimen no. 21 failed at 228640 cycles.

All the specimens used for the first set of tests had holes drilled with a backing plates. As Table 9 indicates, the fatigue life varied from 12000 cycles to 17000 cycles.

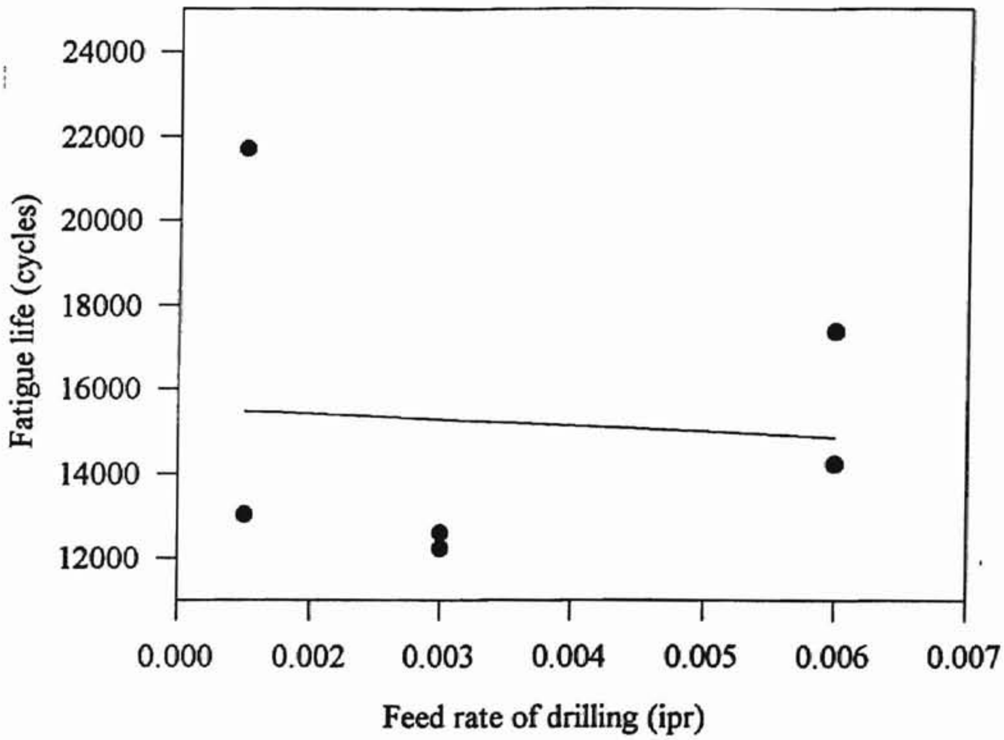

Figure 6 : Effect of feedrate of drilling on fatigue life when the specimen was loaded between 5 KN. and 0.4 KN. The specimens were drilled with a backing plate.

Cycles N	Maximum Load KN.	Minimum Load KN.
0	4.0	0.4
1800	3.9	0.3
7800	3.9	0.2
16200	3.7	0.2
70200	4.1	0.6
100670	4.2	0.6

Table 8: Change in load level as the fatigue test progressed for a specimen initially loaded at 4.0 KN. max and 0.4 KN. min. Hole was drilled with a backing plate. Specimen failed at 100670 cycles. Specimen no. 22.

Specimen no.	Drilling feed rate ipr	Max. Stress	Mean Stress MPa	Min. Stress	Life Cycles
7	0.0015	101.8	55	8.14	13040
10	0.0015	101.8	55	8.14	21700
8	0.003	101.8	55	8.14	12230
11	0.003	101.8	55	8.14	12600
9	0.006	101.8	55	8.14	17380

Table 9 : Fatigue Life of specimens loaded to a maximum load of 5 KN. and minimum load of 0.4 KN. Holes were drilled with a backing plate.

The variations in the fatigue life are due to many factors that have a cumulative effect on the specimens fatigue life. These factors are discussed in the next chapter. As Figure 6 indicates, it is not possible to make any conclusion on the effect of feed rate of drilling on the fatigue life of the specimens tested.

The second set of fatigue tests were also done on specimens with holes drilled with a backing plate. The only parameter that was varied this time was the maximum stress level. It was reduced it to 3.4 KN. so that the specimens had a longer life. The results are shown in Table 10. As we can see from Figure 7 however there is no distinct trend that relates feed rate of drilling to the fatigue lives of the specimens. Additional tests on specimens drilled with a wider range of feed rate is required.

The next set of fatigue tests were performed at an intermediate maximum load of 4 KN. so that the lives of the specimens are of the order of 80,000 to 100,000 cycles. The results are shown in Table 9. The effect of feed rate of drilling versus fatigue life, when the specimen was loaded between 4 KN. and 0.4 KN., is shown in Figure 8.

Specimen no.	Drilling feed rate ipr	Max. Stress	Mean Stress MPa	Min. Stress	Life Cycles
16	0.0015	70	39	8.14	188320
19	0.0015	70	39	8.14	285930
21	0.003	70	39	8.14	228640
15	0.006	70	39	8.14	182080
20	0.006	70	39	8.14	270290

Table 10 : Fatigue Life of specimens loaded to a maximum load of 3.4 KN. and minimum load of 0.4 KN. Holes were drilled with a backing plate.

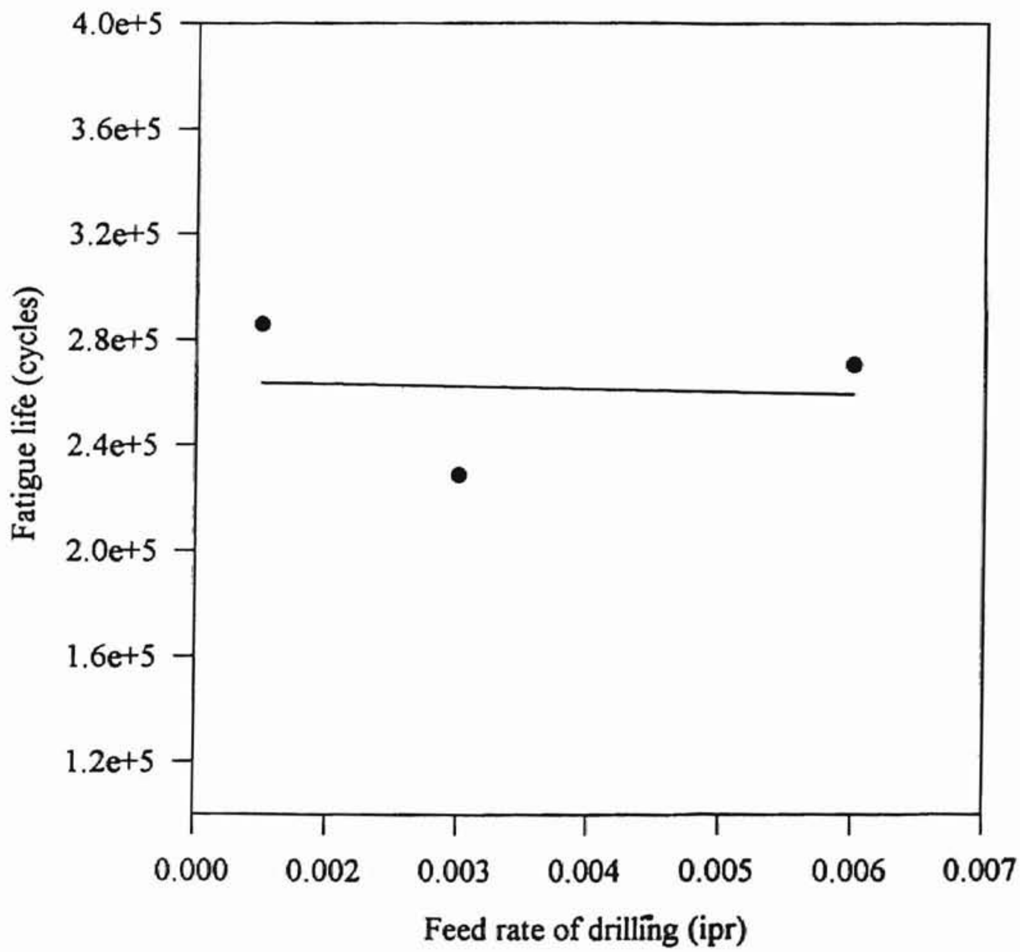

Figure 7 : Effect of feedrate of drilling on fatigue life when the specimen was loaded between 3.4 KN. and 0.4 KN. The specimens were drilled with a backing plate.

It is known that the extent of delamination is smaller when backing pressure is used. However, as Andrews (6) noted, backing pressure is difficult to apply on curved surfaces and in situations where access to the backside is difficult. Accordingly, specimens were prepared with holes that were drilled with no backing pressure, and fatigue tests performed at a maximum load of 3.4 KN. The results are given in Table 12.

Specimen no.	Drilling feed rate ipr	Max. Stress	Mean Stress MPa	Min. Stress	Life Cycles
22	0.003	81.4	44.79	8.14	100670
36	0.0015	81.4	44.79	8.14	83720
35	0.006	81.4	44.79	8.14	80399

Table 11 : Fatigue Life of specimens loaded to a maximum load of 4 KN. and minimum load of 0.4 KN. Holes were drilled with a backing plate.

Specimen no.	Drilling feed rate ipr	Max. Stress	Mean Stress MPa	Min.Stress	Life Cycles
24	0.0015	70	39	8.14	171910
39	0.0015	70	39	8.14	180900
25	0.003	70	39	8.14	136090
21	0.003	70	39	8.14	228640
26	0.006	70	39	8.14	126360
40	0.006	70	39	8.14	125780

Table 12 : Fatigue Life of specimens loaded to a maximum load of 3.4 KN. and minimum load of 0.4 KN. Holes were drilled without a backing plate.

As the Table 12 indicates, there are two interesting findings. Firstly, the life of

Specimen no.	Drilling feed rate ipr	Max. Stress MPa	Mean Stress MPa	Min.Stress MPa	Life Cycles
28	0.006	70	39	8.14	125450
30	0.0015	70	39	8.14	112700

Table 13 : Fatigue Life of specimens loaded to a maximum load of 3.4 KN. and minimum load of 0.4 KN. Holes were drilled without a backing plate. They were injected with epoxy adhesives

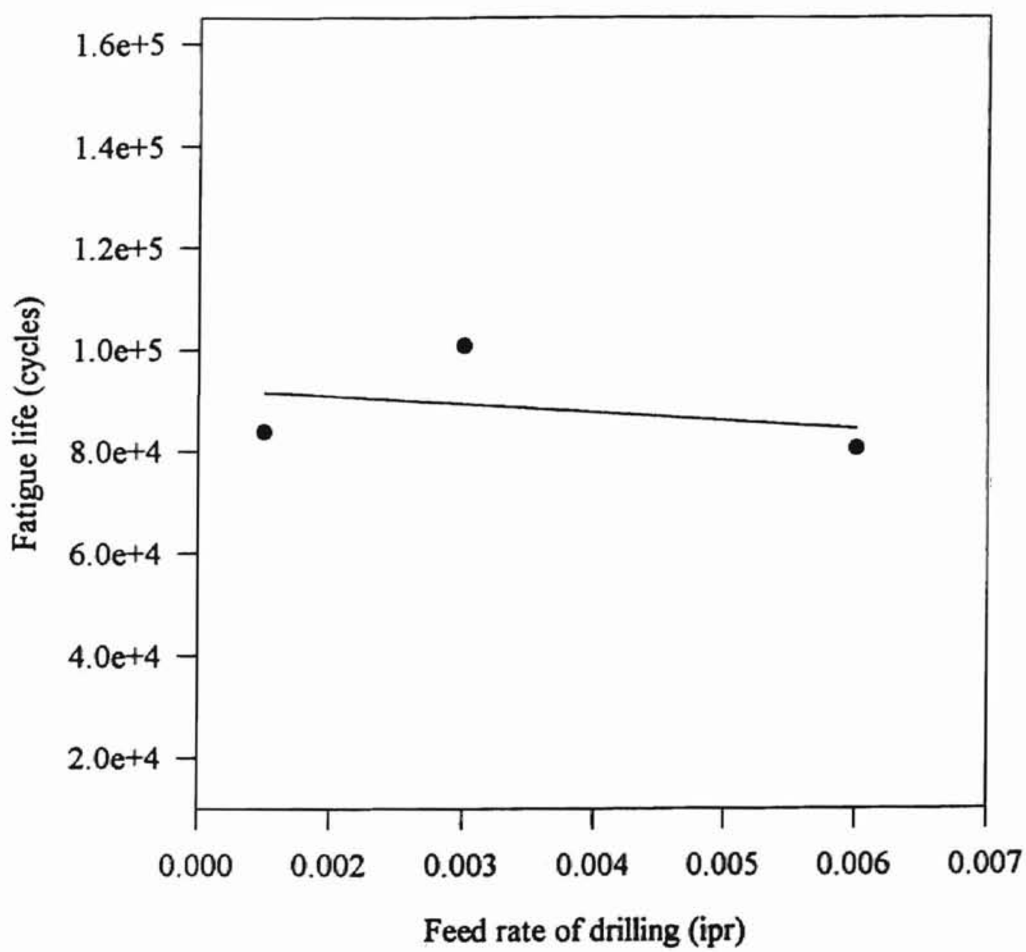

Figure 8 : Effect of feedrate of drilling on fatigue life when the specimen was loaded between 4 KN. and 0.4 KN. The specimens were drilled with a backing plate.

the specimens tested were lower than similar tests performed on specimens with holes drilled with backing pressure. Secondly, there was a noticeable difference between the lives of specimens with different drill feed rates. Figure 9 shows the effect of feed rate on fatigue life of specimen drilled without using backing plate is in Figure 9. Also, Figure 10 compares the fatigue life of specimens drilled with and without backing plate.

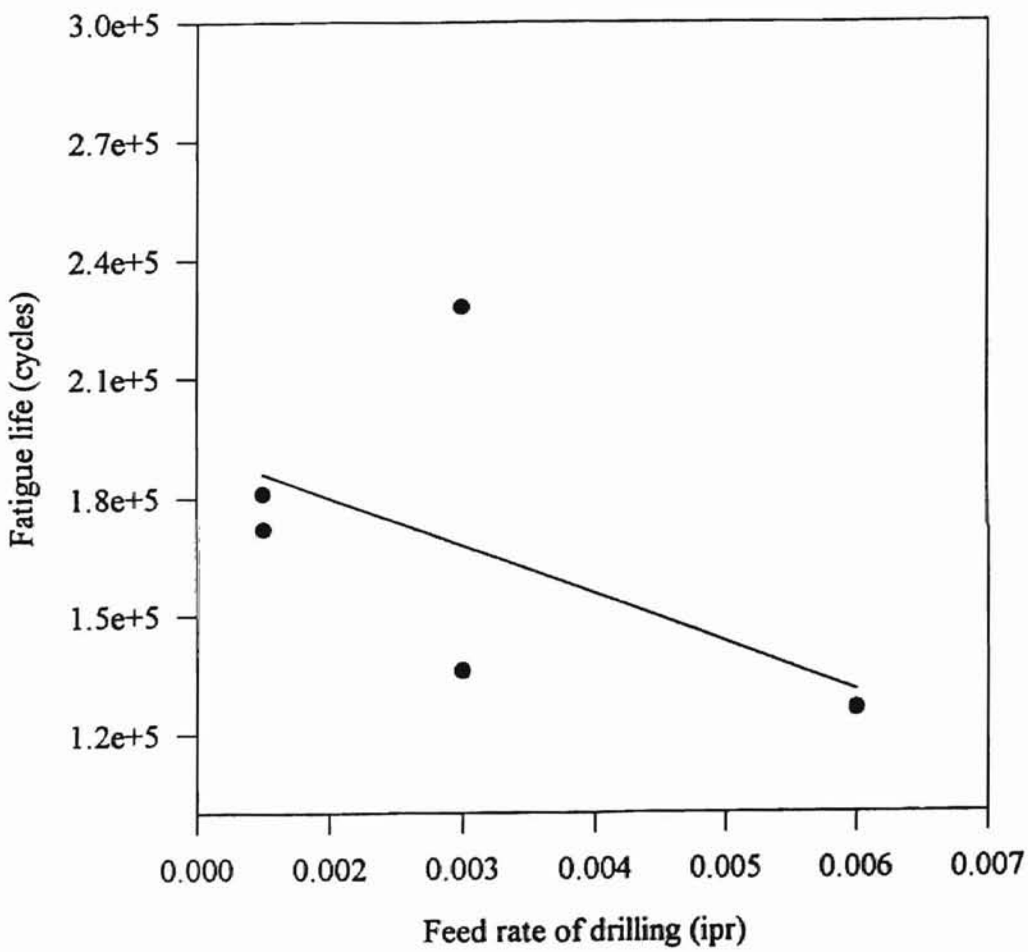

Figure 9 : Effect of feedrate of drilling on fatigue life when the specimen was loaded between 3.4 KN. and 0.4 KN. The specimens were drilled without a backing plate.

It is sometimes difficult to control parameters like feed rate, drilling speed etc. in an industrial environment since maximizing productivity is their main goal. An alternative to controlling the drilling parameters would be to perform simple and fast

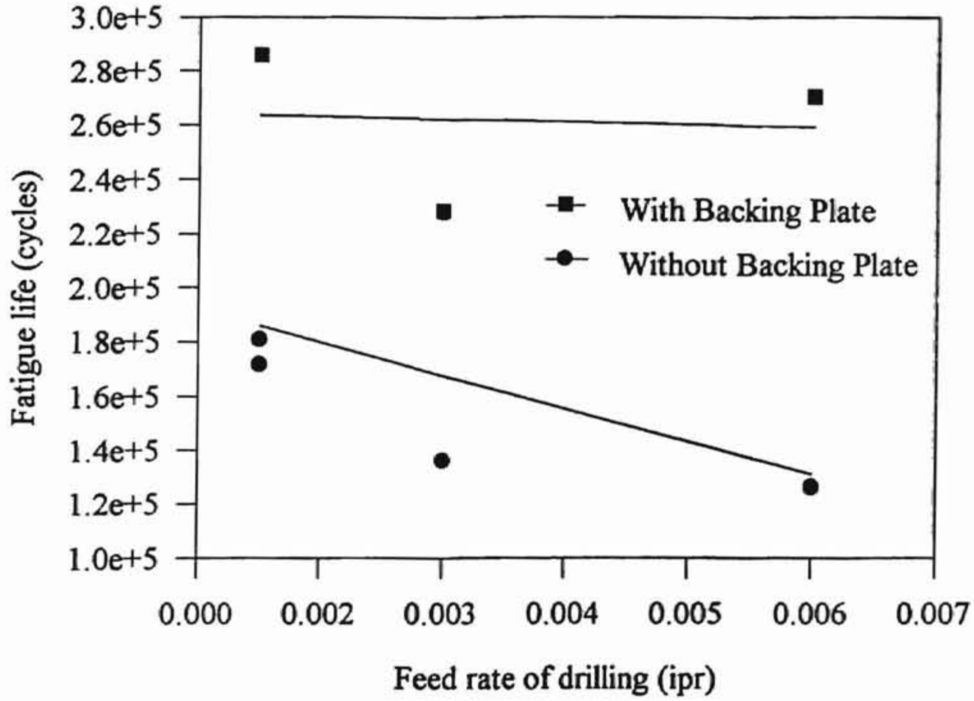

Figure 10 : Comparison between fatigue lives of specimens loaded between 3.4 KN. and 0.4 with and without a backing plate.

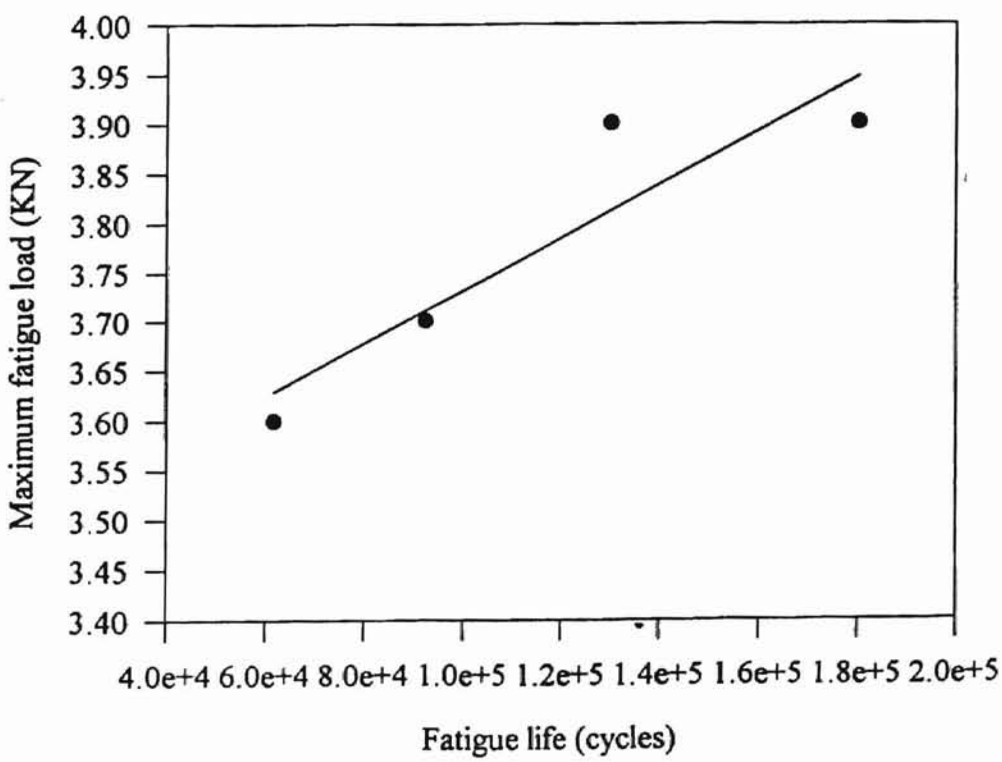

Figure 11 : Change in maximum stress level as the fatigue test progressed. The initial maximum load was 3.4 KN. or a maximum stress of 70 MPa.

repair of the drilled hole. Since the major damage in drilling is in the form of delamination, a high strength adhesive could be used to fill up these voids so that the fatigue life of the specimen is increased. The next set of experiments were performed on specimens with resin injected after the hole was drilled. Two different epoxy adhesives were used in an attempt to find the most effective one. The results of these tests are shown in Table 13. The failed specimens were observed under the zoom microscope to observe any penetration of the adhesive into the laminate. However there was no noticeable adhesive penetration, which could be due to insufficient pressure applied on the adhesive.

During the fatigue tests, the change in maximum and minimum loads was monitored with respect to time. It was observed that at higher stress level of 102 MPa the stress tended to decrease with time . On the other hand when the tests were performed at lower maximum stress of 70 MPa, the stress tended to increase with time. The variation of stress levels as the test progresses is shown in Figures 5 and 11.

Photographs were taken of the drilled holes and the fractured surface. Figure 12 to 23 are photographs of the top and bottom surface of the specimen showing the drilled hole. It is clear from the photographs that increase in feed rate increases the extent of surface damage. Damage at the point of entry of the bit is less than that at the point of exit. Use of backing plate improved the quality of the hole drilled. Some care is needed in examining these photos since the damage on the opposite side shows up too.

Figure 24 to 27 show the damage zone for fatigue tests performed at different testing conditions. These photographs indicate that the damage zone depends on the maximum fatigue stress. The damage zone for low cycle fatigue is much more than that for high cycle fatigue.

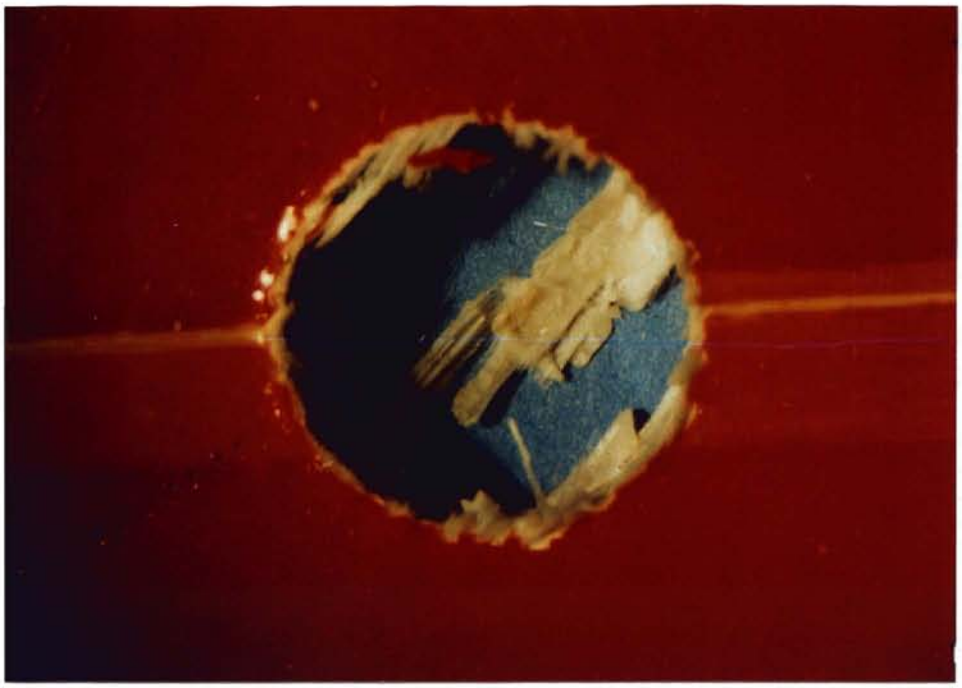

Figure 12 : The entry face of a hole drilled at a feed rate of 0.0015 ipr, without a backing plate. x 8

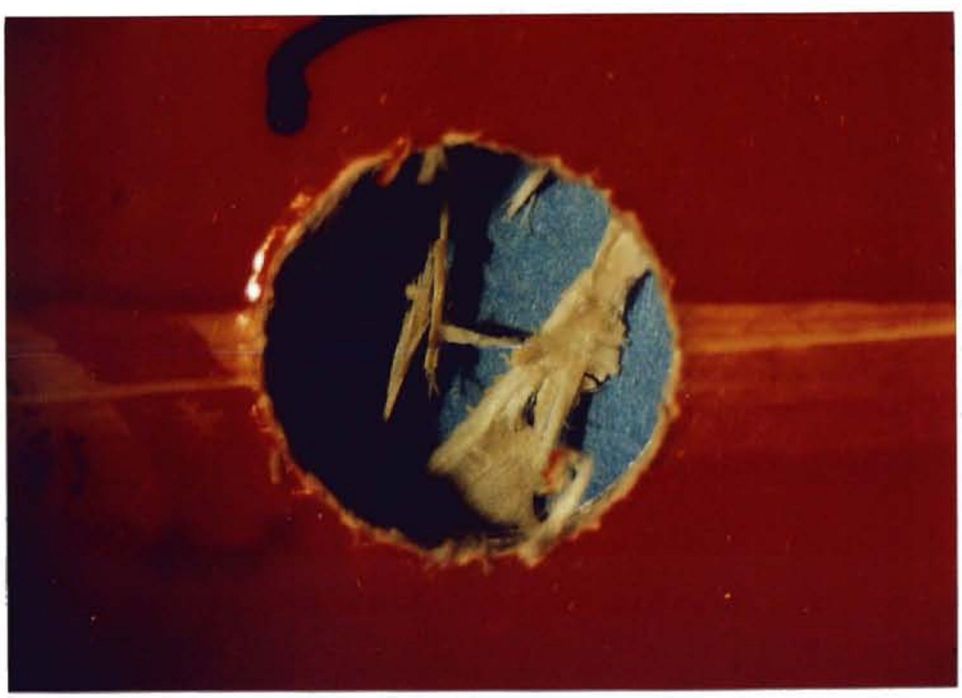

Figure 13 : The entry face of a hole drilled at a feed rate of 0.003 ipr, without a backing plate. x 8

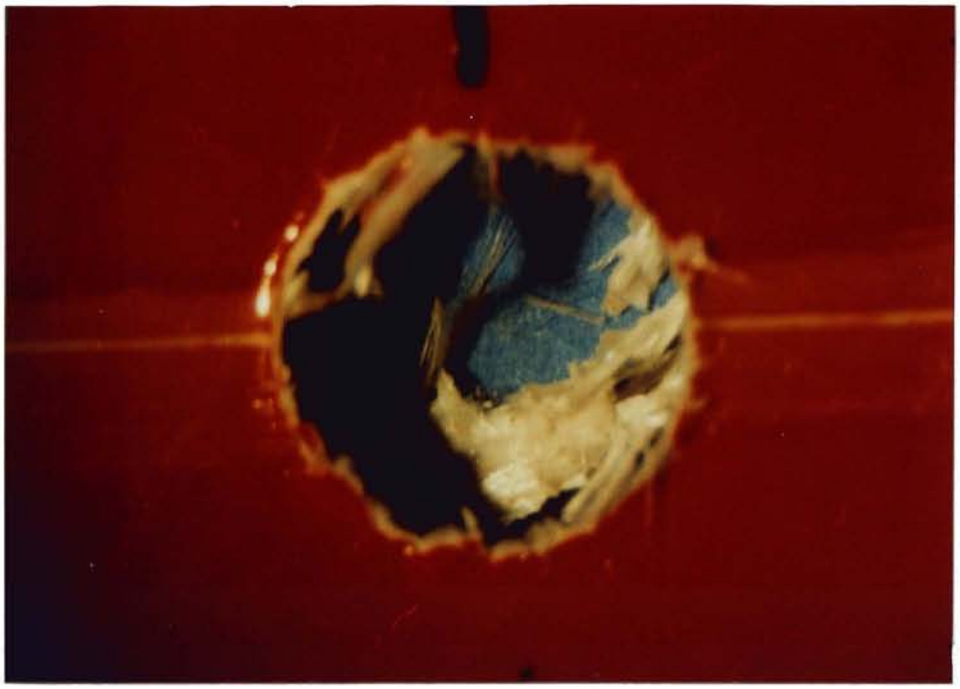

Figure 14 : The entry face of a hole drilled at a feed rate of 0.006 ipr, without a backing plate. x 8

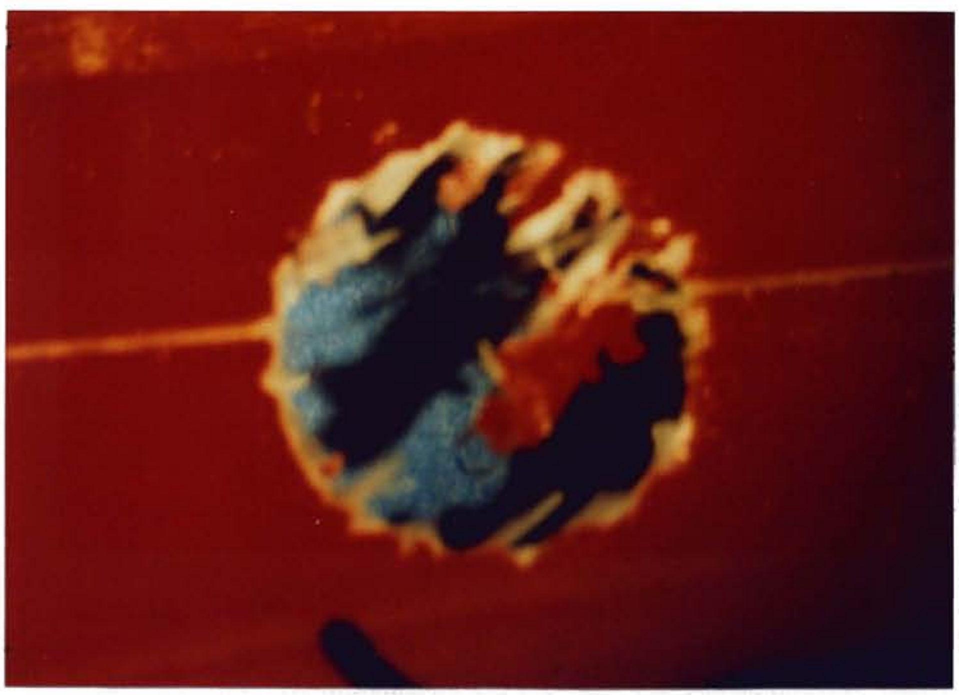

Figure 15 : The exit face of a hole drilled at a feed rate of 0.0015 ipr, without a backing plate. x 8

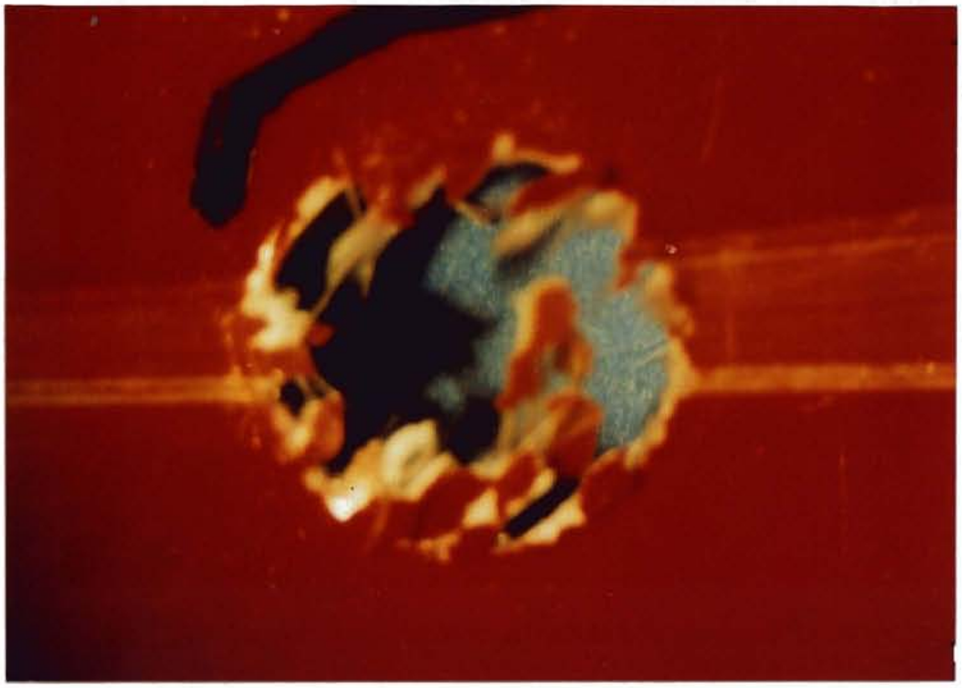

Figure 16 : The exit face of a hole drilled at a feed rate of 0.003 ipr, without a backing plate. x 8

Figure 17 : The exit face of a hole drilled at a feed rate of 0.006 ipr, without a backing plate. x 8

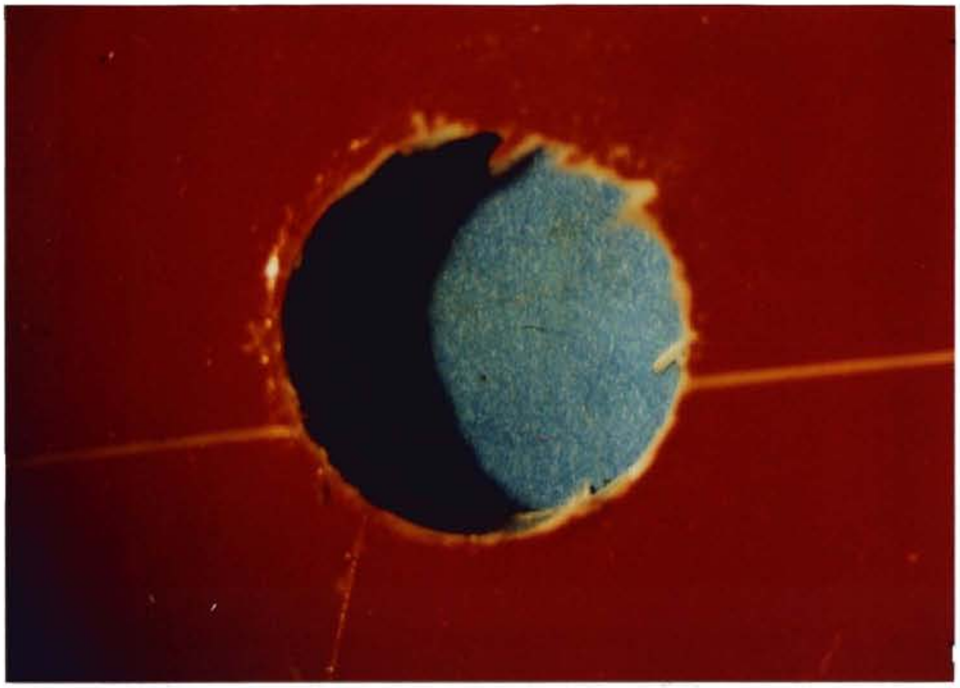

Figure 18 : The entry face of a hole drilled at a feed rate of 0.0015 ipr, with a backing plate. x 8

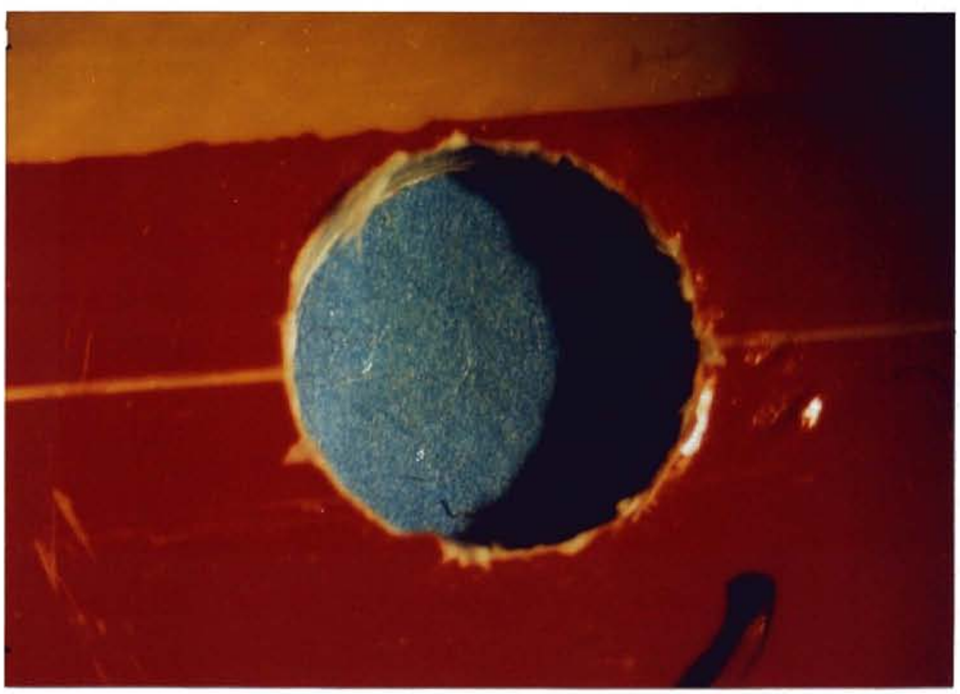

Figure 19 : The entry face of a hole drilled at a feed rate of 0.003 ipr, with a backing plate. x 8

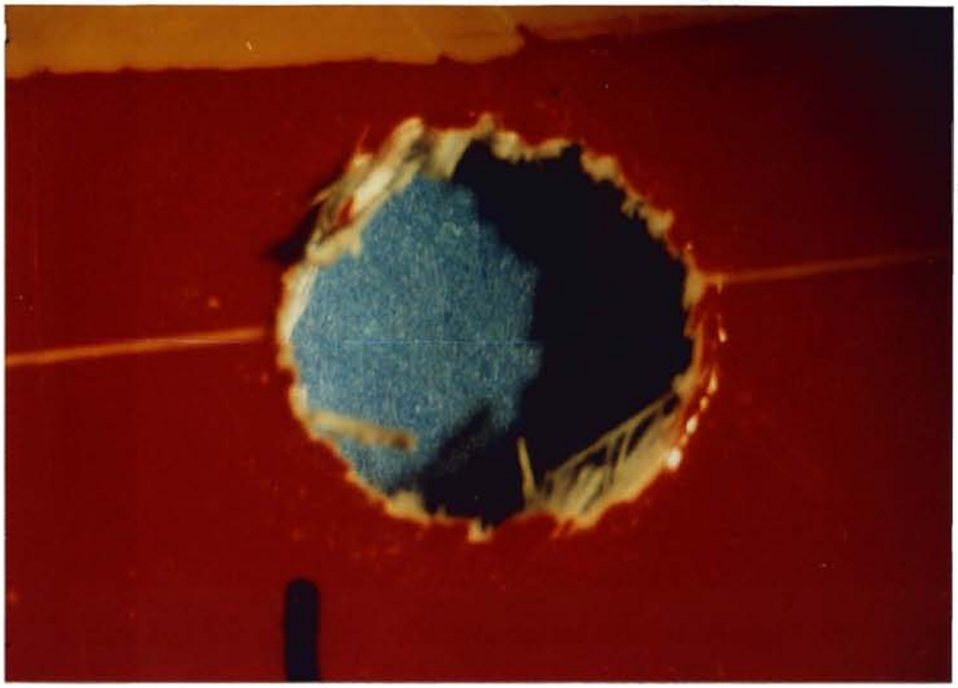

Figure 20 : The entry face of a hole drilled at a feed rate of 0.006 ipr, with a backing plate. x 8

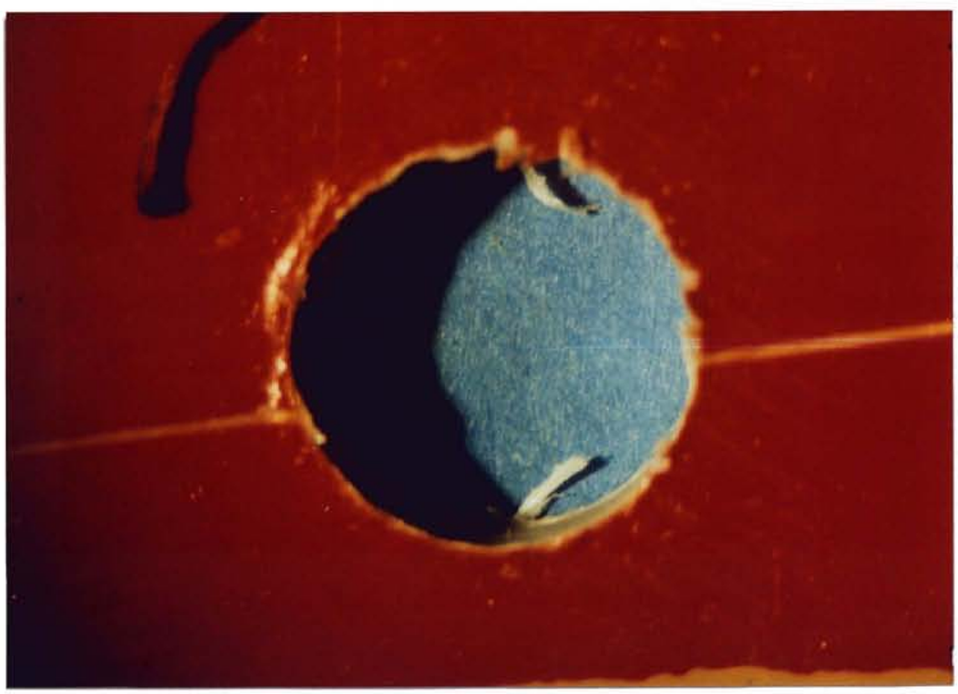

Figure 21 : The exit face of a hole drilled at a feed rate of 0.0015 ipr, with a backing plate. x 8

Figure 22 : The exit face of a hole drilled at a feed rate of 0.003 ipr, with a backing plate.

x 8

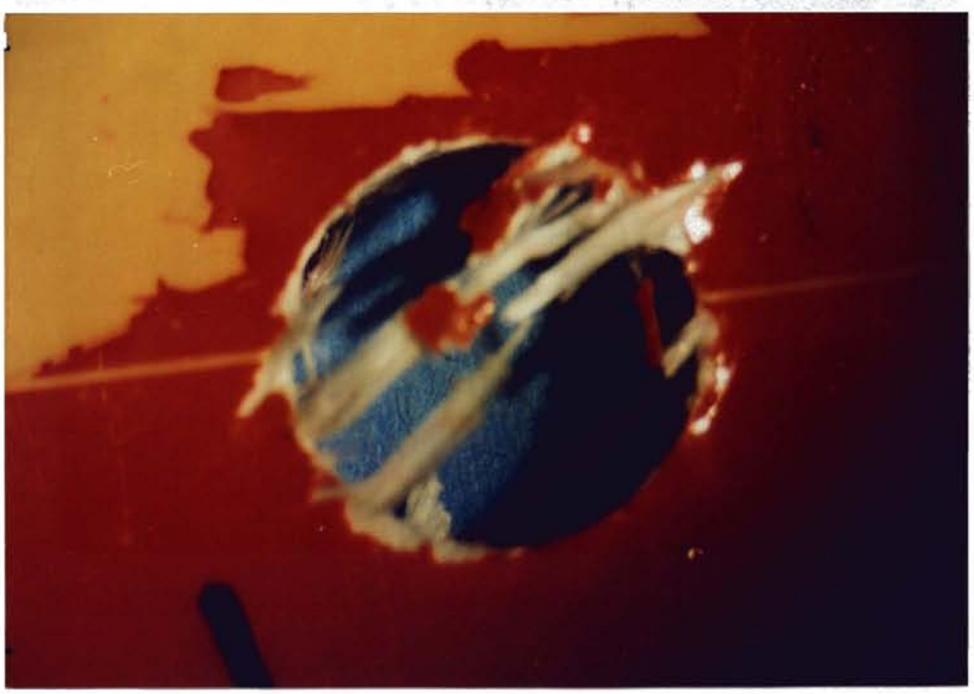

Figure 23 : The exit face of a hole drilled at a feed rate of 0.006 ipr, with a backing plate.

x 8

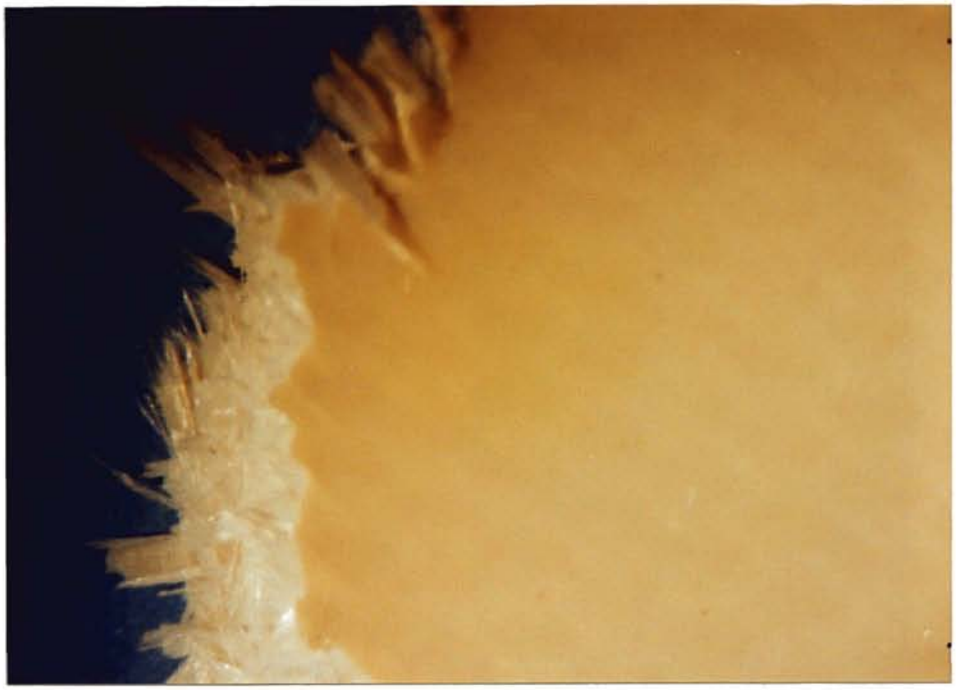

Figure 24 : The top face around the failed area, of a fatigue specimen, with 0.25 inch hole drilled at 0.006 ipr with a backing plate. The specimen failed at 270290 cycles. The maximum stress was 3.4 KN. x 7

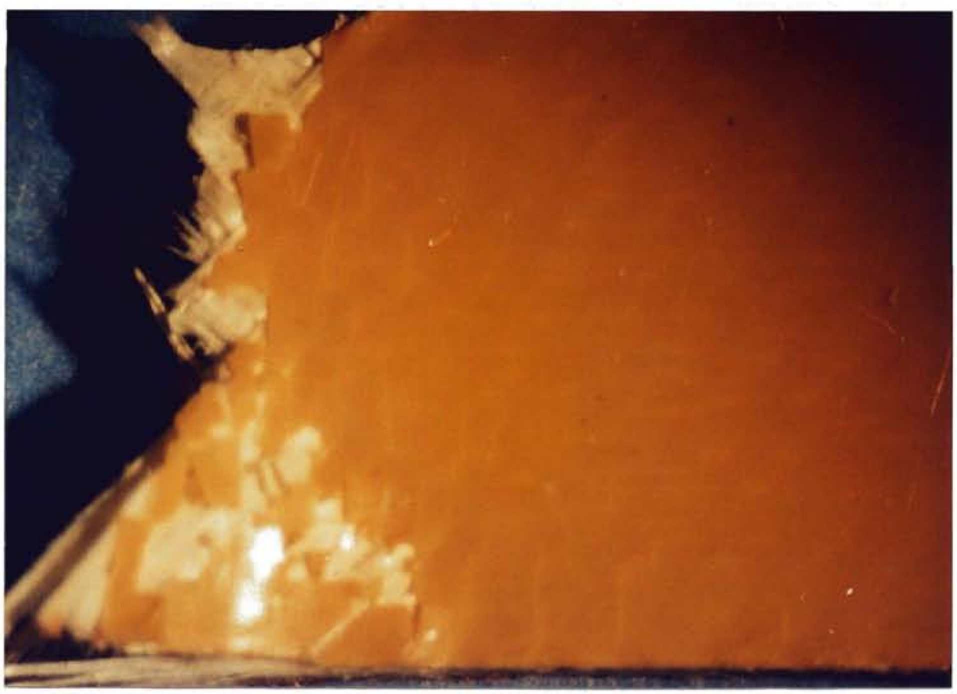

Figure 25 : The top face around the failed area, of a fatigue specimen, with 0.25 inch hole drilled at 0.003 ipr without a backing plate. The specimen failed at 136090 cycles. The maximum stress was 3.4 KN. x 7

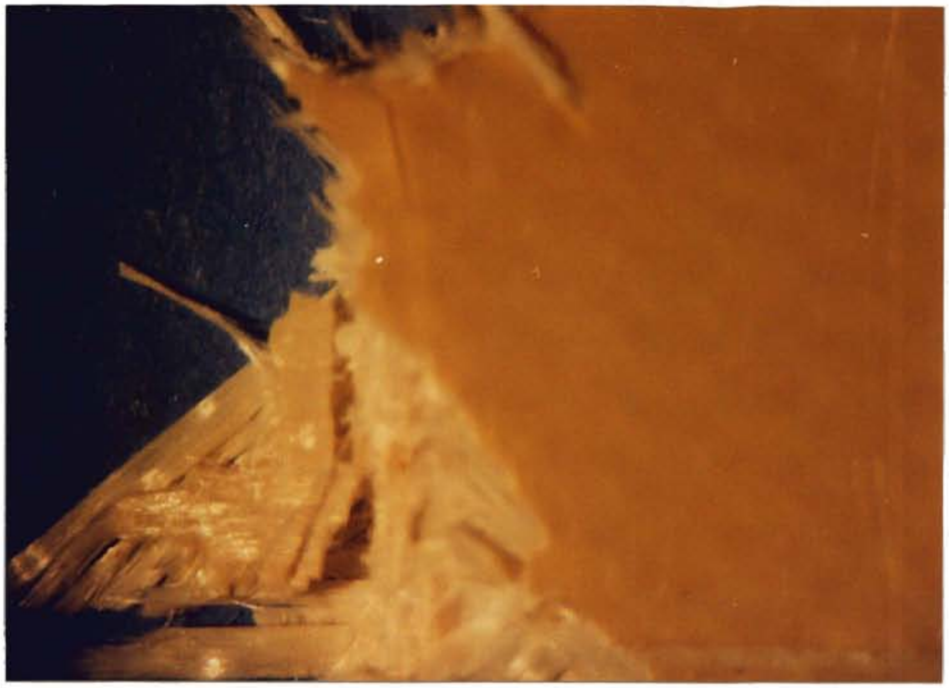

Figure 26 : The top face around the failed area, of a fatigue specimen, with 0.25 inch hole drilled at 0.006 ipr with a backing plate. The specimen failed at 17380 cycles. The maximum stress was 5 KN. x 7

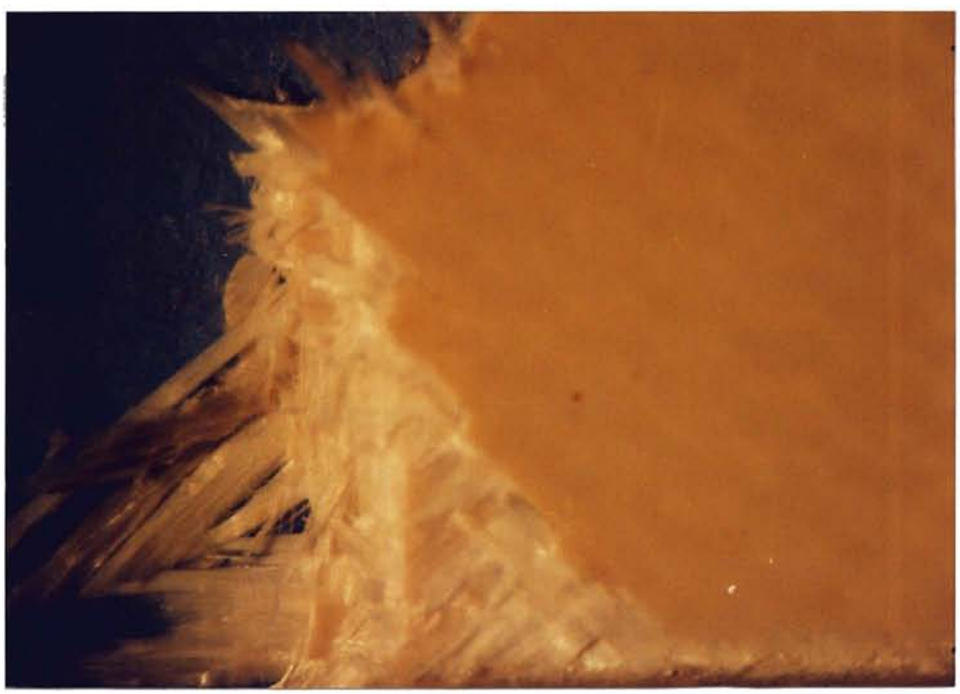

Figure 27 : The top face around the failed area, of a fatigue specimen, with 0.25 inch hole drilled at 0.003 ipr with a backing plate. The specimen failed at 12600 cycles. The maximum stress was 5 KN. x 7

The fractured and drilled surfaces were also observed under the scanning electron microscope. Figure 28 shows the fractured surface and a part of the drilled surface. It can be observed that the fractured surface is uneven and has regions that are delaminated. Also, observe the extensive damage of the top layer of the specimen. Figure 29 shows a section of the hole surface shown in Figure 28, that indicates inter laminar delamination. Crazing can be observed on the matrix surface at the fatigue initiation zone in Figure 30. Also, note the matrix adhering to the broken fibers. Figure 31 shows the increase in irregularity in the overload zone as compared to the fatigue zone that starts from the edge of the hole(Figure 28). The top and bottom surface seen in Figure 32 and 33, show extensive damage. Note that since this specimen was drilled without a backing plate the bottom layer is damaged more than the top layer. Also, note that the bottom layers look more smeared, with the matrix layer almost not visible.

Figure 34 and Figure 35 show the top and bottom layers of a hole surface drilled with a backing plate; note that both the layers show nearly the same amount of damage. Figure 36 shows the damage in the top surface, extending from the hole towards the edge of the specimen. Also note that the damage is almost planar as against the rest of the fractured area. Figure 37 shows the section of specimen no. 26 through the hole. The hole was drilled without a backing plate at 0.006 ipr. Note the difference in the surface quality of the drilled and the cut surface which is to the left. Also note that along with visible delamination, the hole surface is conspicuously smeared. The section was cut using a slow speed diamond saw.

Figures 38 to 43 are photographs of the hole surfaces drilled under different conditions. These are representative drilled hole surfaces away from the top and bottom layers of the specimen. However appreciable variation in hole surface quality was observed in all the specimens around the hole periphery. The following points can be observed from these photographs.

1. The change in feed rate had an impact on the quality of the hole. As the feed rate increased, the quality of the hole surface deteriorated. However, the difference in the quality of the holes drilled at 0.006 ipr and 0.003 ipr was more pronounced than that between 0.003 and 0.0015 ipr.
2. The absence of backing plate led to an increase in the smearing of the drilled surface. The specimens drilled with backing plate had a better finish than those drilled without a backing plate. Delamination can easily be observed in Figure 40, as against in Figure 43, due to the laminar interface being obscured by the cut and broken glass fibers.

The SEM was also used to observe the differences in the fractured surfaces of tensile specimens. In Figure 44 and 45 we can observe that almost all the fibers have traces of matrix on them. This indicates relatively good fiber matrix adhesion. Both the figures show almost the same amount of matrix adhering to the broken glass fibers. Although the photos show only a small portion of the fractured surface, almost all the fibers had matrix adhering to it. Hence no definite conclusion could be made regarding the variation of fiber matrix adhesion with respect to the strain rate of the tensile test.

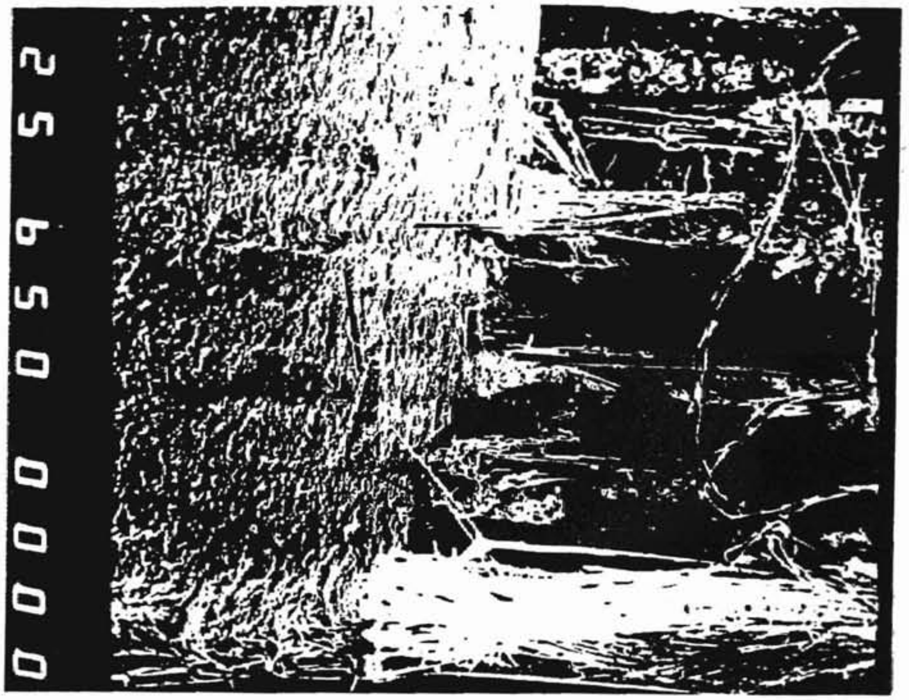

Figure 28 : Section showing the hole surface to the left and fractured surface. The hole quality is poor and the fractured surface is very uneven. This is specimen no 25, was drilled with no backing plate at 0.003 ipr and failed at 136090 cycles. x 65

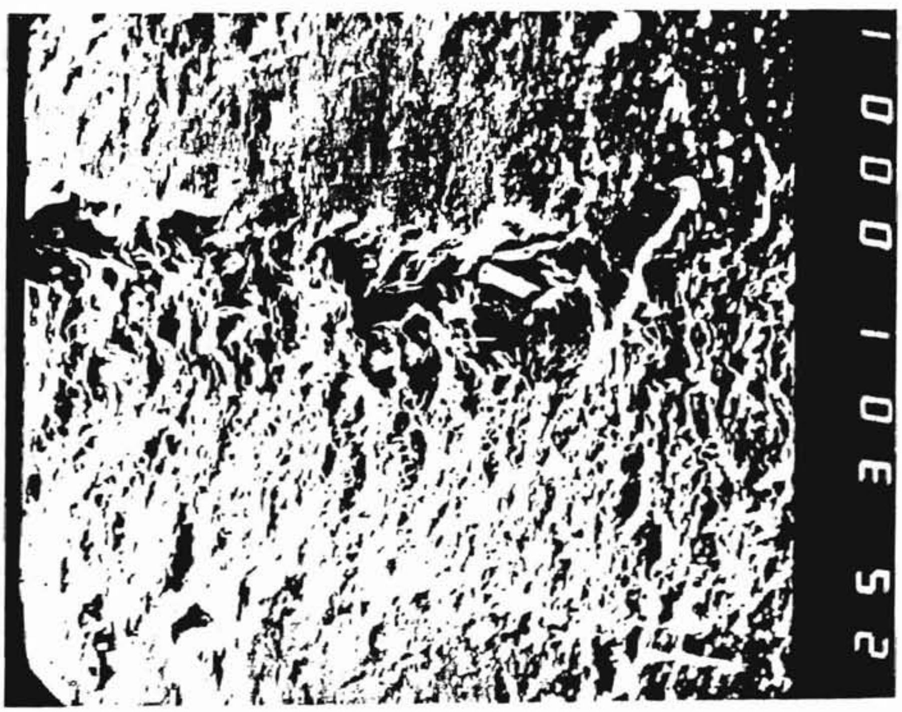

Figure 29 : A detail from figure 28 showing interlaminar delamination of the hole surface. x 300

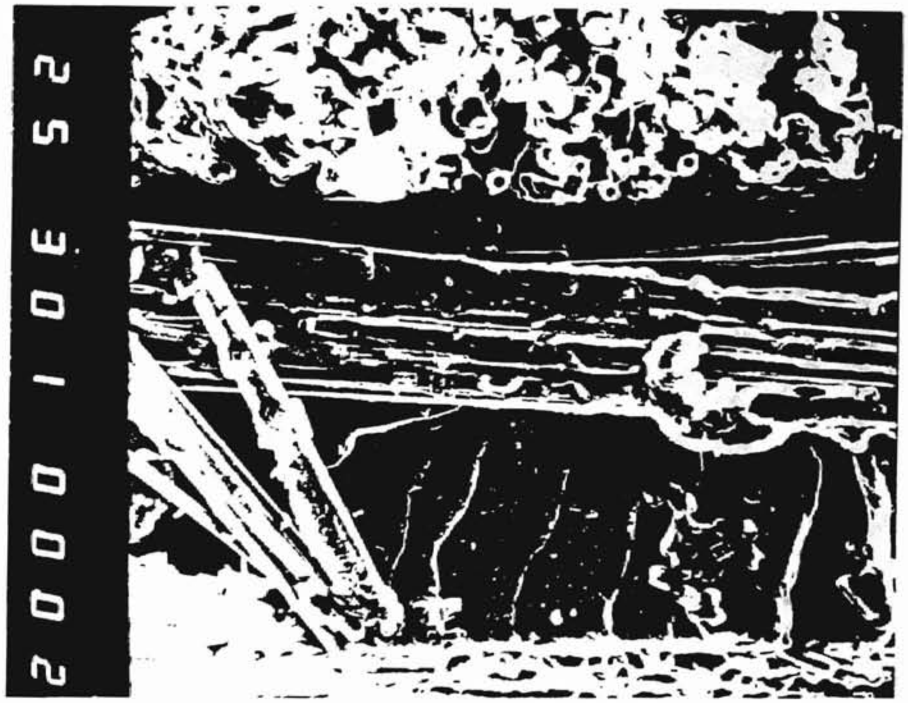

Figure 30 : Crazing of the matrix near the fatigue initiation zone for specimen no. 25. Observe too, the matrix adhering to the broken glass fibers. x 300

Figure 31 : The fractured area near the edge (overload zone) of the specimen no. 25. Extensive fiber pull out can be observed. x 65

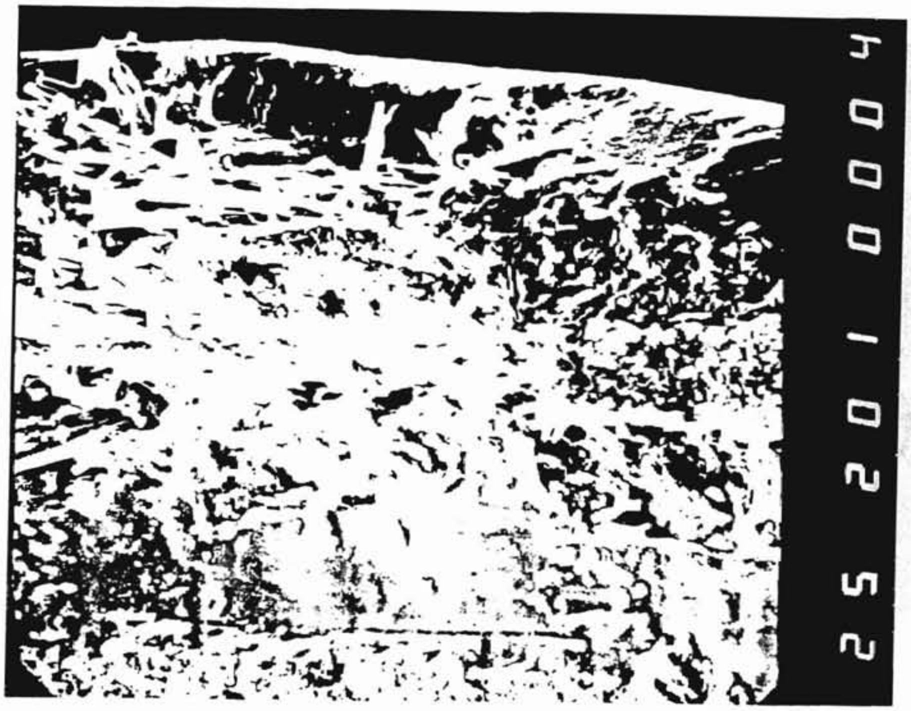

Figure 32 : The top layer of the hole surface of specimen no. 25. Extensive damage can be observed. x 200

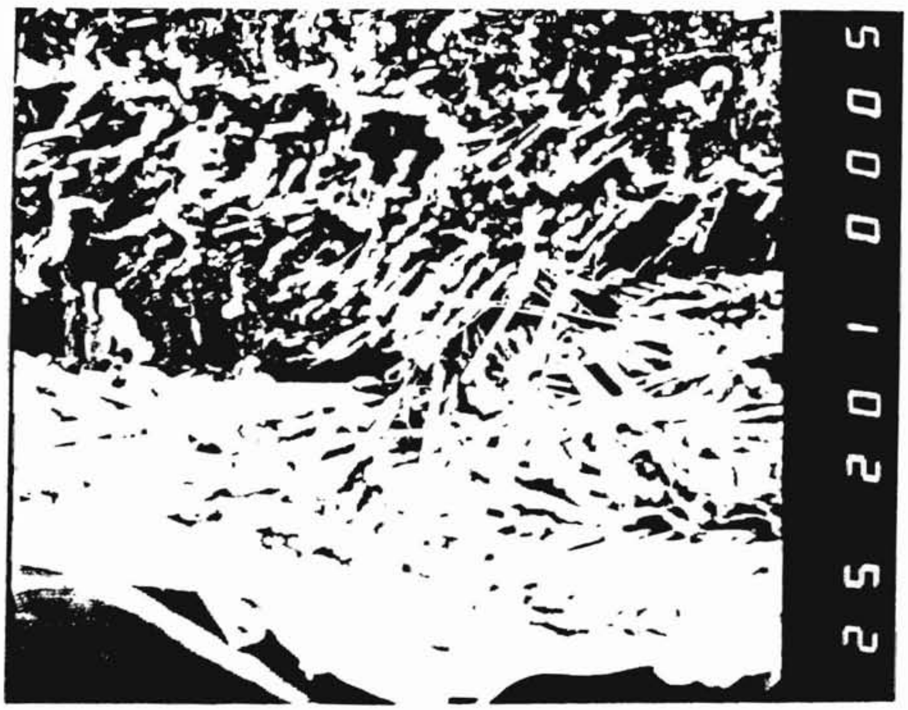

Figure 33 : The bottom layer of the hole surface of specimen no. 25. It is apparent that the damage is much more than that in Figure 32. x 200

Figure 34 : The top layer of the hole surface of specimen no. 13. The hole was drilled with a backing plate and the feed rate was 0.006 ipr. x 200

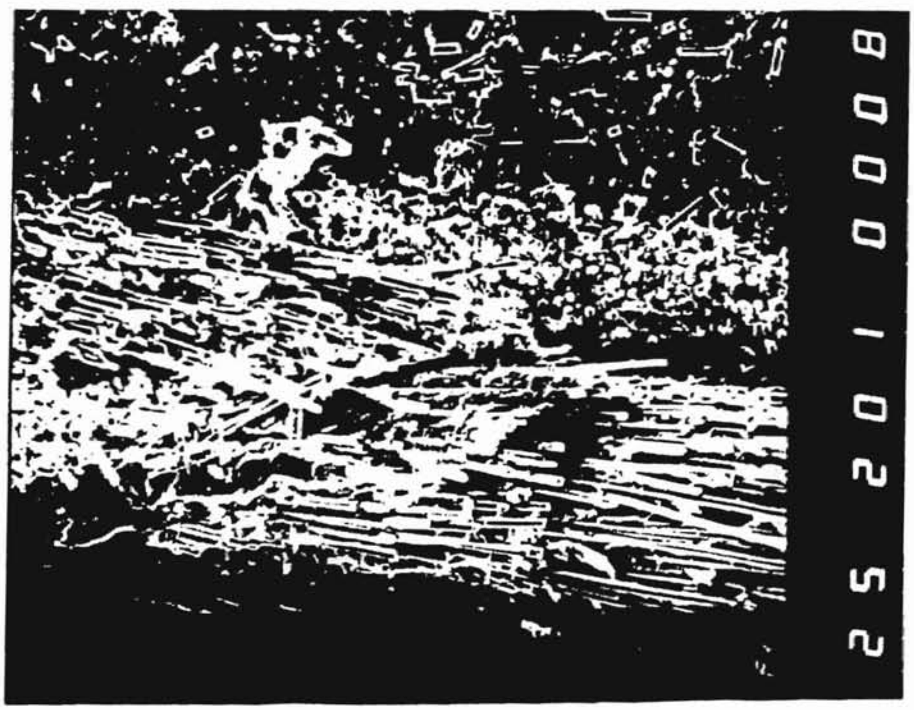

Figure 35 : The bottom layer of the hole surface of specimen no. 13. Note that the damage is almost equal to that in Figure 34. x 200

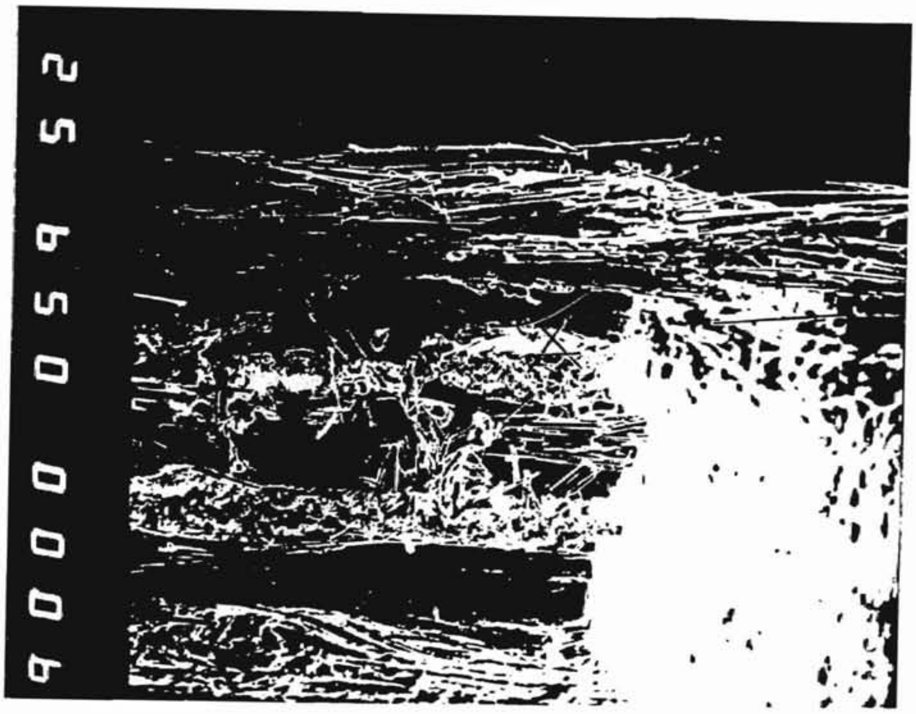

Figure 36 : The fractured surface of specimen 25 shows a planar failure of the top layer, extending from the hole towards the edge. x 65

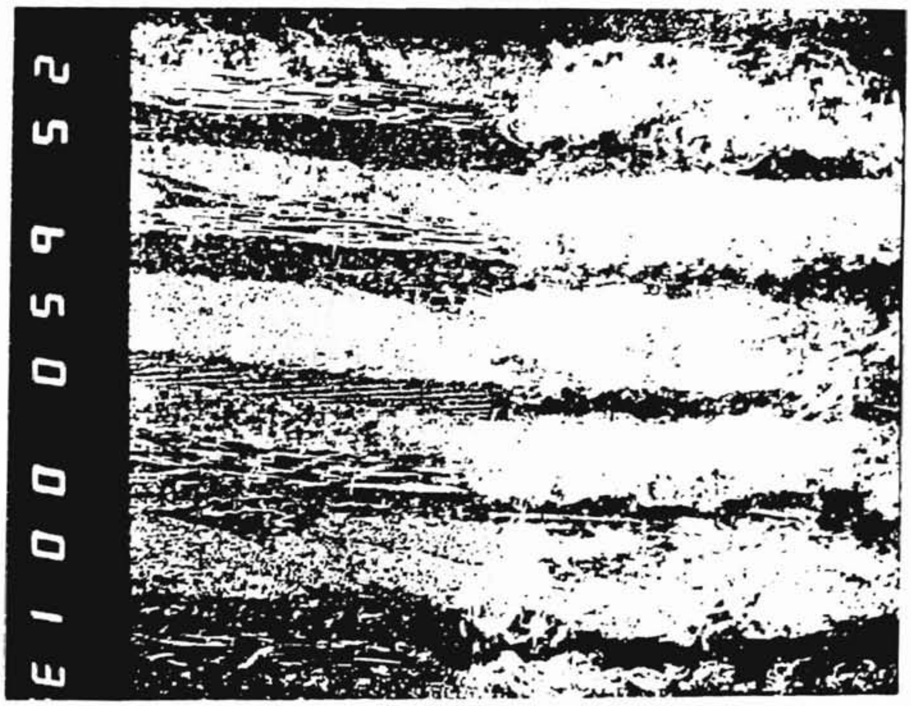

Figure 37 : The cross section of specimen 26 sawn through the hole showing the damage in the hole surface. Note the smearing of the drilled surface in the right. x 65

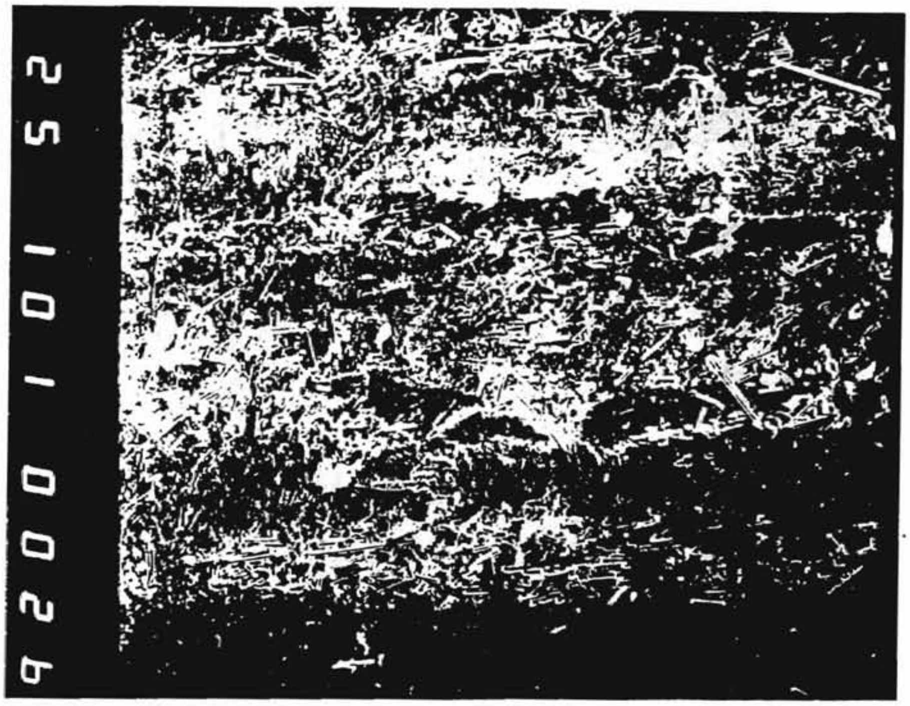

Figure 38 : Sectional view of the hole surface drilled at 0.0015 ipr with a backing plate. x 100

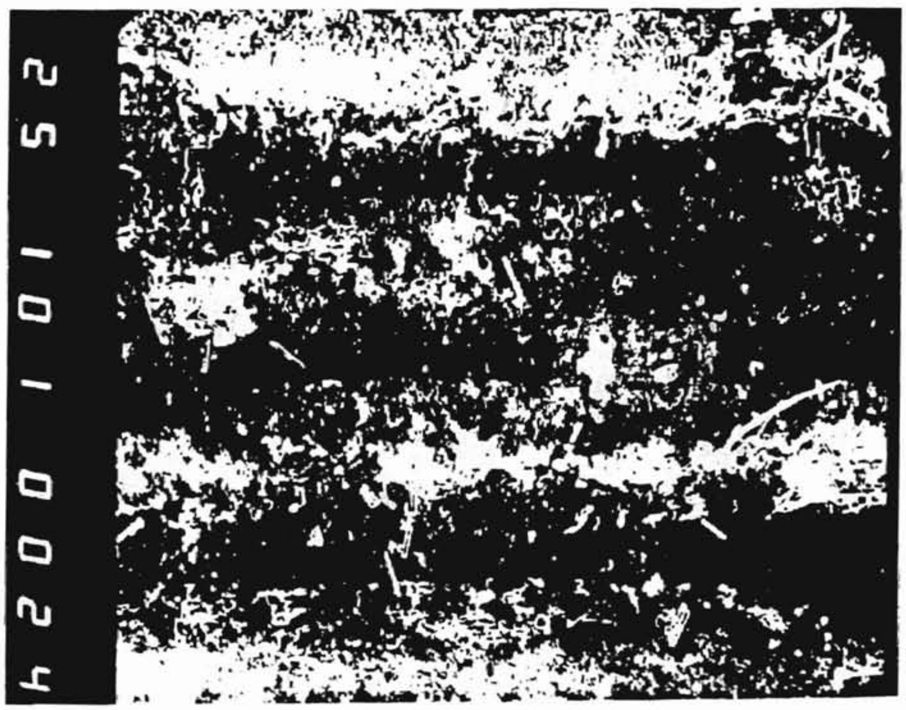

Figure 39 : Sectional view of the hole surface drilled at 0.003 ipr with a backing plate. x 100

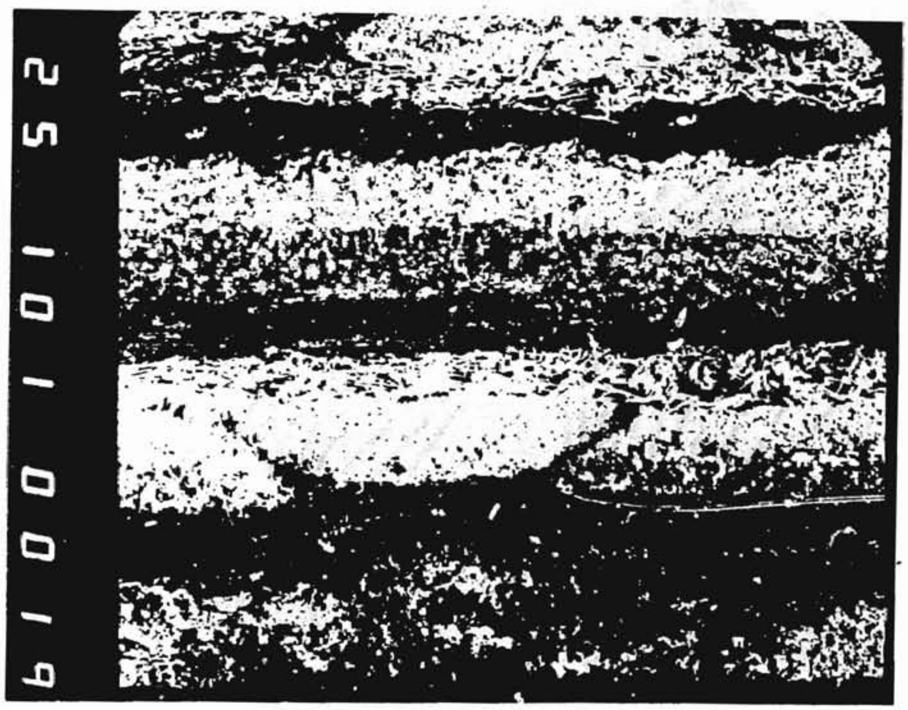

Figure 40 : Sectional view of the hole surface drilled at 0.006 ipr with a backing plate. x100

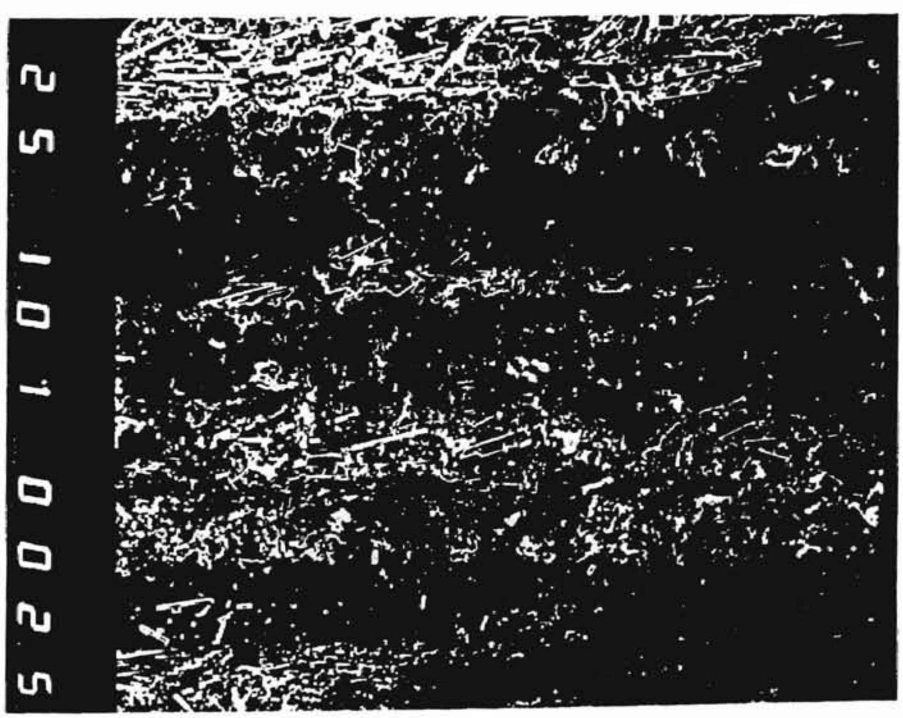

Figure 41 : Sectional view of the hole surface drilled at 0.0015 ipr without a backing plate. x 100

Figure 42 : Sectional view of the hole surface drilled at 0.003 ipr without a backing plate.

x 100

Figure 43 : Sectional view of the hole surface drilled at 0.006 ipr without a backing plate.

x 100

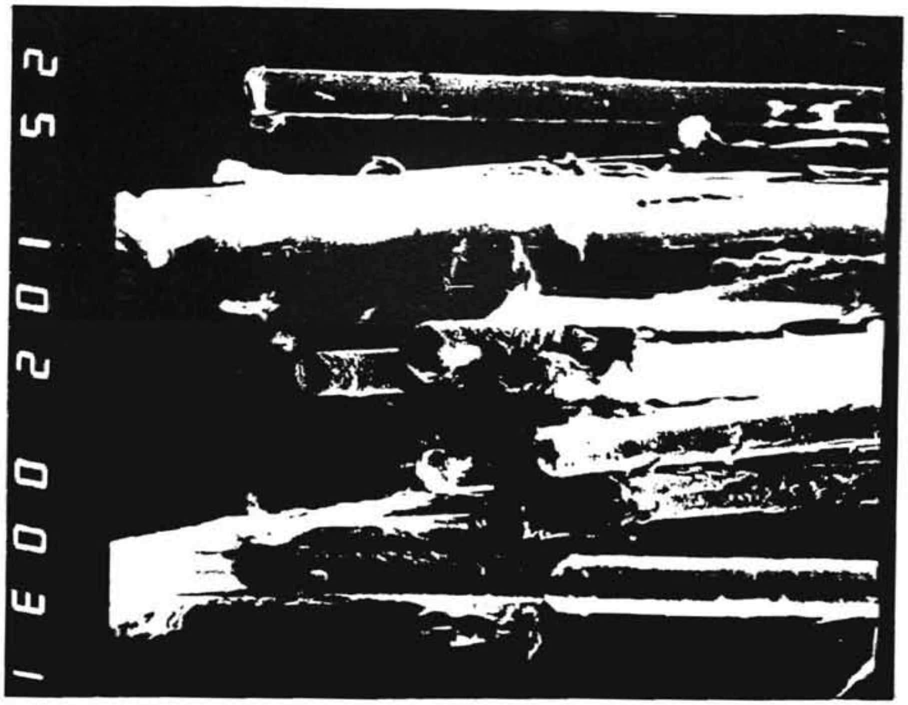

Figure 44 : Fracture surface of a tensile specimen tested at 0.0127 mm/sec. Section shown is near the edge of the specimen. x 200

Figure 45 : Fracture surface of a tensile specimen tested at 0.1524 mm/sec. Section shown is near the edge of the specimen. x 200

CHAPTER 5

DISCUSSION

Almost 40 tests were performed during the duration of this research. The three main out comes of interests explored are 1) Effect of feed rate on the tensile strength of the composite, 2) Effect of feed rate on the fatigue life of the composite, 3) Effect of backing plate on the fatigue life of the composite, and 4) Repair of the drilling induced damage using resin injection technique. These would be discussed in turn. The first set of experiments was performed to determine the strength of the composite being used. The tensile tests were performed at three different strain rates. It is seen from Figure 4, that strain rate has an appreciable effect on the strength of the specimen. Curtis P. T. (12) found that strain rate had a significant effect on GRP. However he was not able to explain this phenomenon satisfactorily. He suggested that the strain rate sensitivity was due to the environmental sensitivity of the glass fibers.

Kander et. al., (18) studied the changes in damage accumulation and energy absorption as a function of strain rate in a glass reinforced polypropylene composite during uniaxial tensile testing. They performed tensile tests at various strain rates and found that the strength increased with increasing strain rate. Their results show that the viscoelastic response of the matrix resin and the "apparent" fiber-matrix interface properties changed dramatically as a function of strain rate, and were closely coupled to the balance between the time scale of the fiber pull out process and the characteristic time scale of resin deformation. They observed that, at low strain rates, relatively poor fiber matrix adhesion was observed in the presence of a relatively "ductile" matrix resin. However, at faster strain rates, relatively good fiber matrix adhesion was observed in the presence of a relatively "brittle" matrix resin. A "ductile-to-brittle" transition was observed at intermediate rates where both mechanisms were in competition.

The mechanical properties of polymers vary with temperature. Most polymers are relatively brittle below the glass transition temperature (T_g). The T_g of polypropylene is approximately -15° C and that of PPS is 85° C. Since, at room temperature, polypropylene is above the T_g and PPS is below the T_g the two should have different mechanical behavior despite the fact that both are thermoplastics. However, Figure 43 and 44 show extensive fiber matrix adhesion indicating a more ductile behavior of the matrix. Boyer (19) studied the energy damping spectra for semicrystalline polymers at various temperatures normalized to T_g. He observed the presence of several damping peaks for the material, prominently the b peak at $T = 0.75T_g$. Boyer (19) observed that unlike other polymers, polyphenylene oxide (PPO) had a remarkably high impact strength throughout the temperature range of -200° C to +100° C. The polymer was extremely tough even in the absence of a strong low temperature b damping peak. In this study, the PPS matrix, which would be similar to PPO, shows ductile failure in the form of crazing. Hence, the observations for polypropylene/glass fiber composite might explain the strain rate effects observed in the PPS/glass fiber composite used here.

It is unfortunate that a much wider range of feed rates could not be achieved. With only a factor of four available, feed rate of drilling did not have any noticeable effect on the strength of the specimens with holes drilled with backing plate or without backing plate. Yau, S.-S and Chow, T.-W., (20) investigated the open hole tensile strength on PEEK reinforced carbon fibers. They concluded that; woven-fabric composite specimens with molded holes have higher strength than those with drilled holes. In this study, however, since the change in feed rate in small, any effect here is minor compared to the strain rate effect discussed above. A reminder is appropriate that in all cases the top and bottom fiber layers were extensively damaged during drilling. The effect of feed rate is more likely to be observed during fatigue tests because the surface quality should influence fatigue crack initiation and initial crack propagation.

Fatigue tests were the main focus of this research. The results indicate there is a significant spread of data. Spread in fatigue data of FRP composites has been observed by numerous researchers (21-23). The spread of data is usually attributed to the inherent material and manufacturing anomalies. For example, details of the precise fiber cross over location with respect to the plies and local discontinuities like fiber spacing and inefficient fiber matrix bonding. These would effect the crack initiation due to fiber rupture. Other factors that might have contributed are :

1) The inconsistency of the specimen quality. The quality of the specimen depends on the accuracy of the machine and fixtures used and the skill of the machinist.
2) The misalignment of the fatigue specimen in the jaws that grip the specimen. Any misalignment would result in less than 100 % axial loading. This in turn would change the fatigue life of the specimen.

The first set of fatigue tests was performed on specimens with holes drilled with a backing plate. Using a backing plate decreases the extent of damage. This was evident from the fact that the fatigue lives of the specimen were longer than those made with no backing plate (Figure 10). This was true at all the stress levels for which the tests were performed. Researchers (1 and 3), have emphasized that thrust force applied during drilling has a significant impact on the fatigue life of a specimen. The backing plate imparts added stiffness to the laminate so that change in thrust does not have a significant impact on the hole quality. The backing plate which is sacrificially allowed to delaminate provides sufficient thickness to minimize delamination of the bottom plies of the laminate. Thus specimens drilled with backing plates have relatively small difference in damage at the three feed rates, which in turn results in small variation in fatigue life.

For the next set of tests, specimens with holes drilled without a backing plate were used. It is observed that the fatigue life was shorter than comparable specimens drilled with backing plate. Also, in these specimens, feed rate of drilling had a noticeable impact on the fatigue life (Figure 9). As the feed rate increased, the fatigue life of the specimen decreased. In the absence of a backing plate, the specimen bends due to the applied thrust. In this case, when the drilling operation first begins, the thickness of the laminate is sufficient to withstand the thrust force. As the tool approaches the exit plane, the stiffness provided by the remaining plies may not be sufficient to withstand the thrust force. Hence the plies at the bottom flex out. Depending on the thrust force, the flexing out may cause may cause initiation and propagation of the delamination crack (3). Thus, increasing the feed rate results in an increase in the thrust force consequently, resulting in more damage.

The resin injection technique used to repair the damage done during drilling. However no positive effect on the fatigue life was noticed, results of which are in Table 13. In hindsight :

1) The pressure used to inject the adhesive might be insufficient. Hence, little resin was able to penetrate into the matrix so as to fill any delamination present.

2) The viscosity of the adhesives used was probably high. If lower viscosity adhesives were used then the adhesive would be able to be absorbed by he fibers due to capillary action.

Finally, during the fatigue tests it was observed that the stress level in the specimen changed with time. Normally, it is seen that as the specimen undergoes damage, the stress level decreases. This is because the strength of the specimen decreases with the increase in damage and correspondingly, decreasing the stress level. However, it was observed that this was only true for the highest stress level of 101 MPa. For tests performed at the lowest stress level of 70 MPa, the stress level actually increased with time (Table 7). The tensile strength of the matrix material PPS, is about 82 MPa. According to Hertzberg (24), crystalline polymers exhibit Type V stress-strain behavior. When these polymers are loaded below their tensile strength, initial yielding occurs along with a general breakdown of the original crystalline structure within the polymer. Since fatigue does not go beyond the maximum strain level, the matrix does not fail. The drawn chains of the polymer realign themselves to form highly oriented, and strong units. It should be noted however, that there is a localized area around the hole that has a stress level of 6σ (420 MPa for $\sigma = 70$ MPa), much higher than the strength of the matrix, due to stress concentration (25). Despite this, a large percent of the matrix still probably undergoes strain hardening. The matrix transmits the load between fibers but does not carry much load. However a stronger and less plastic matrix could restrict the movement of the fibers consequently increasing the stress level in the composite. The fact that at stress levels above the tensile strength of the matrix, the stress levels decrease, fortifies the above discussion.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results obtained from this research conform to those of other researchers (13,14,18). The composite strength was found to be strain rate sensitive, however, feed rate of drilling did not effect the strength of the composite. The matrix was somewhat ductile and the fracture surface had glass fibers with significant matrix adhesion. The use of backing plate was found to reduce the amount of damage induced during drilling. The fatigue life of the composite drilled with backing plate was relatively unaffected by feed rate when maximum stresses ranged between 30 to 50% of the tensile strength.

For specimens drilled without backing plates, the fatigue life was shorter than those drilled with a backing plate. For specimens drilled without backing plate, the feed rate did have a noticeable impact on its fatigue life. During fatigue tests performed at a maximum stress of 3.4 KN., the stress level increased slightly with time. This behavior is believed to be due to the strain hardening of the surrounding matrix that restricts the movement of the reinforcing glass fibers.

The conclusions from this investigation are as follows :

1) The tensile strength of the composite increases as the strain rate increases.

2) Feed rate of drilling in the range 0.0015 ipr to 0.006 ipr does not effect the tensile strength of the composite.

3) Feed rate of drilling effects the fatigue life of the composite when holes are drilled without a backing plate. An increase in feed rate results in increased damage, and consequently decreases the fatigue life. This effect was not observed for those specimens that were drilled with a backing plate.

4) The use of backing plate decreases the damage caused due to drilling. The fatigue life of these specimen were higher than for those without backing plates.

5) The properties of the matrix have a major influence on the fatigue behavior of polymer composites. At maximum stresses below the tensile strength of the matrix, some of the matrix near the vicinity of the hole is believed to strain harden. Thus, a stronger and less plastic matrix restricts the movement of the glass fibers around them resulting in an increase in stress levels.

6) The effectiveness of the resin injection technique could not be ascertained due to little penetration of the viscous resin into the specimen.

Recommendations

1) Feed rate of drilling has a significant impact on hole surface quality. In order to determine the relationship between feed rate and hole surface quality it is necessary to perform tests over a much wider range of feed rates.

2) The effect of feed rate of drilling on fatigue life for other comparable composite systems like carbon fiber reinforced PPS or glass fiber reinforced epoxy should be investigated. This would help understand the damage mechanism involved during drilling of composites laminates.

3) Resin injection technique needs to be explored further. Resins with lower viscosity, and a higher injection pressure could be used. Better resin penetration should decrease delamination and in turn increase the fatigue life.

4) The effect of other more stiffer backing plate materials on the drilled hole surface quality and its consequent effect on fatigue life should be investigated. A stiffer backing plate should improve the hole surface quality.

5) The strain rate dependence of the tensile strength in other composites materials should be studied. This would help understand better, the role played by the matrix in determining the tensile strength of the composite.

6) Effect of other tool designs and materials on hole surface quality should be investigated. Better tool designs and tool materials should decrease the amount of damage incurred during drilling consequently increasing the fatigue life.

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