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# Impact Damage Resistance of Carbon/Epoxy Composite Tubes for the DC-XA Liquid Hydrogen Feedline

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# Impact Damage Resistance of Carbon/Epoxy Composite Tubes for the DC-XA Liquid Hydrogen Feedline

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**TABLE OF CONTENTS**

## LIST OF ILLUSTRATIONS



## LIST OF TABLES

TECHNICAL PAPER

# IMPACT DAMAGE RESISTANCE OF CARBON/EPOXY COMPOSITE TUBES FOR THE DC-XA LIQUID HYDROGEN FEEDLINE

## I. INTRODUCTION

As part of a technology demonstration program between NASA's Marshall Space Flight Center and McDonnell Douglas Aerospace of Huntington Beach, CA, a composite element is to be constructed that will transport liquid hydrogen ($LH_2$) on the *Delta Clipper* (DC-XA) single-stage-to-orbit (SSTO) vehicle. This piece of hardware will be called the $LH_2$ composite feedline (or more simply just "feedline") throughout the remainder of this report.

Among the technologies to be demonstrated by the feedline are:

- Acceptable hydrogen permeability levels for flight hardware
- Composite elbows (90° and 45° bends in tubes).

The feedline was designed by McDonnell Douglas who also selected the composite material to be used. The composite material chosen to construct the feedline is IM7/8552 eight-harness weave prepreg. The feedline consists of two major tubular elements, both approximately 2 inches in diameter. One of the tubes contains a 45° elbow and the other tube contains a 90° elbow. These tubes are joined with a splice tube about 2 inches long. This splice tube is made of unidirectional IM7/8552 prepreg.

The lay-up pattern for the woven prepreg material to manufacture the tubular sections is [0/90, ±45, ±45,0/90] which will give a wall thickness of approximately 0.056 in.

The threat of low-velocity impact damage has always been a key issue when dealing with composite materials. For this program, this is especially true since permeability tends to be the driving property of the composite feedline rather than mechanical strength (see ref. 1). Before composites experience any mechanical loss of properties, matrix cracking will occur. This matrix cracking can give rise to the creation of leak paths within the material that can cause excess permeation.

Unfortunately, the very mechanism that causes composites to have superior fatigue resistance (the creation of many small microcracks that are quickly blunted) tend to cause a composite to become permeable. Thus, a liner is typically situated inside a composite vessel that must have a low permeability rate since structural composites are not designed to be sealants. It is desirable in cryogenic applications to eliminate the liner if possible to minimize the problems that will arise with the mismatch in coefficients of thermal expansion between the composite and the liner. It is a goal of this program to see if this approach may be feasible.

## II. TEST PROGRAM

The test program consisted of inflicting low-velocity impacts on sections of two 90° elbow pieces of the composite feedline. One of the elbow pieces was reserved for sharp tip impacts to simulate such events as screwdriver heads or corners of structures that the feedline may come in contact with. The other elbow piece was subjected to blunt type impacts to simulate such events as dropping the tube on a floor or accidentally hitting the tube with the side of a tool.

### A. Sharp Tip Impacts

A drop weight impact apparatus was used to test the composite tubes for damage resistance. A sharp tip was attached to the existing instrumented tip that strikes the specimens. The "sharp" tips were formed from bolts that had been ground down to various levels of "sharpness." The attachment process is shown in figure 1. The tips of these bolts were examined and photographed under a microscope to obtain data on the "sharpness" of the tip. For all of the tips, an impact event would make the tip less sharp than before the event (i.e., the tips lost their "sharpness" with multiple impacts).

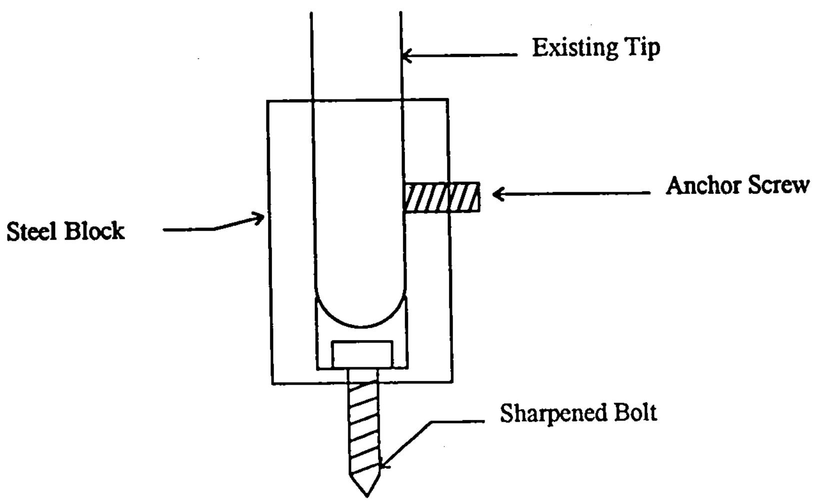



Figure 1. Method of obtaining sharp tipped impacts.

A preliminary hit was made on one end of the test section of a tube at an impact energy of 3.76 J (2.77 ft-lb) since this was estimated to give a damage zone barely visible to the unaided eye. It was found that this level produced clearly visible damage and subsequent impacts were performed with lower incident energies. After each impact, the tube section was pressurized with argon gas, and a water-based leak detector was placed on the impact site to check for leakage. In order to accomplish this, both ends of the tube were sealed off, a nozzle for the pressurized gas at one end and a pressure gauge at the other, as shown in figure 2.

If the argon gas was escaping, then the liquid leak detector would form a line of small bubbles (larger bubbles for larger leaks) exuding from the impact site. Up to 60 lb/in$^2$ of gas pressure was used to check for leaks.

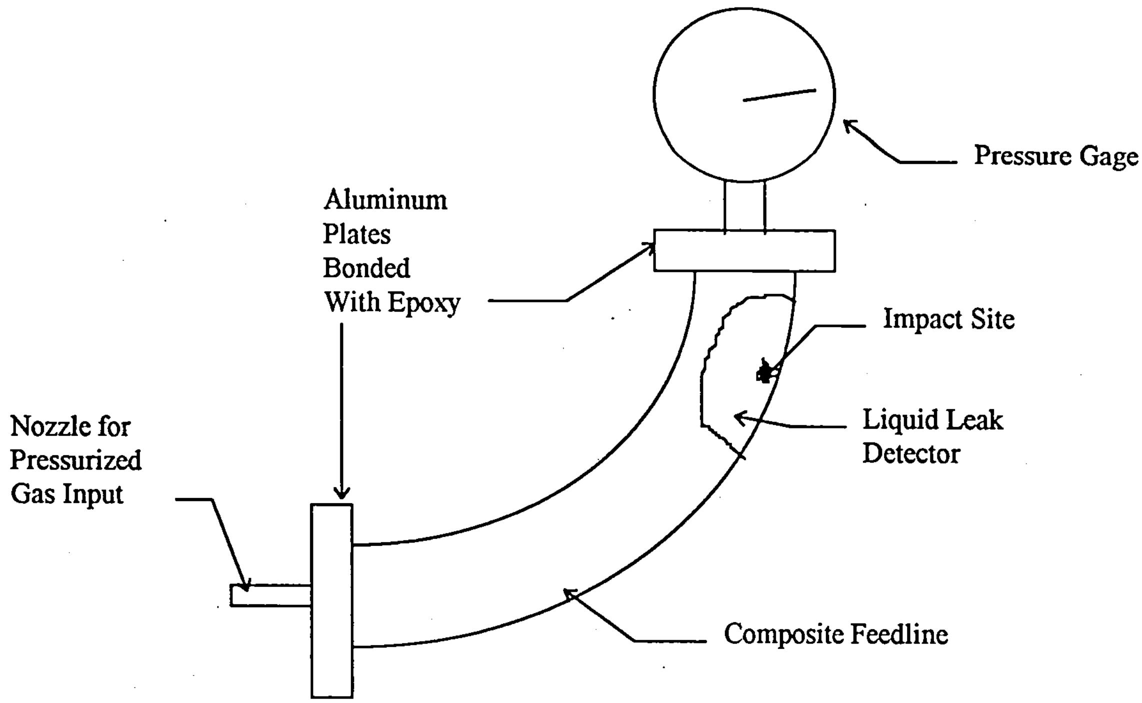



Figure 2. Method of checking for leaks on impacted sections of feedline.

The techniques used in this study will detect relatively large leaks compared to those needed to cause a leak path for hydrogen gas, thus it is understood that the results from this study should not be used for quantitative interpolation of hydrogen gas permeation. The data generated in this report are for qualitative purposes only.

The tube was impacted 19 times at the sites shown in figure 3. Since the damage was highly localized, this large number of hits on one section of tubing was possible.

For the final nine hits, a conical striker that tapered to a 2-mm diameter point was used instead of the sharpened bolts. This was decided since the sharp bolts represented an extreme type of localized damage that allowed penetration of the composite by the tip of the striker. The 2-mm diameter conical indenter was used to obtain data on highly localized damage without penetration of the outer layers of the tube.

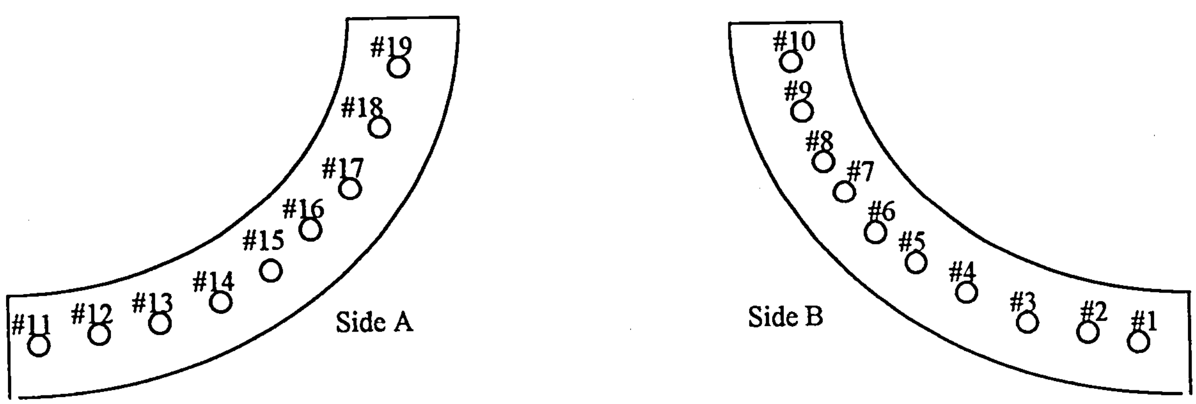



Figure 3. Location of impact sites for sharp impacts.

After the entire tube had been impacted and checked for leaks, photographic documentation of the resulting surface damage was made for the impacts. The impacted areas were then cut from the tube and sectioned for microscopic analyses. The sections were cut through the impact site, and both halves of the sectioned piece were potted in an epoxy resin for polishing before microscopic examination. A fluorescent dye penetrant was placed on the polished specimen that would highlight the matrix microcracking when observed under a black light source and a microscope. Photomicrographic documentation was made on all of the samples. After all of the samples had been initially observed, each sample was ground down approximately another 1 mm and then repolished and analyzed to make certain that the area with the most matrix damage had been inspected. This process was continued on each specimen until the matrix damage became less severe than the previous observation on that particular sample.

## B. Blunt Impacts

A second section of elbow tubing was impact tested using a 0.5-inch diameter semispherically ended rod that was considered a "blunt" type impact compared to the sharpened bolts and conical striker described in the previous section. A total of 16 impacts were conducted on this section of elbow as depicted in figure 4.

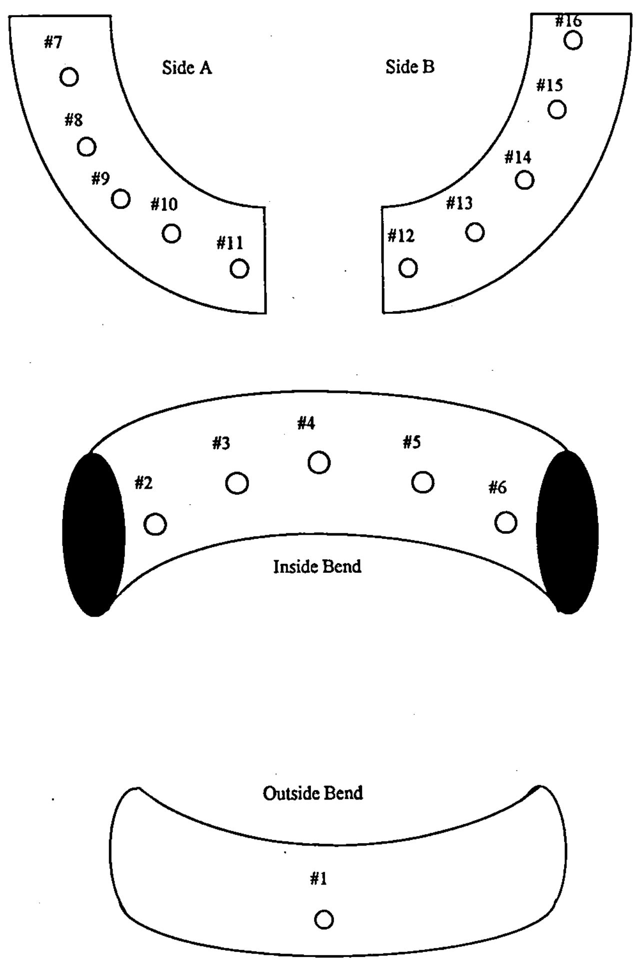



Figure 4. Impact sites for blunt impacts.

The levels ranged from a low of 0.60 J (0.44 ft-lb) to a high of 2.66 J (1.96 ft-lb). After each impact, the tube was pressurized with argon gas and checked for leaks with a soap-type leak detector. Once all 16 impacts were conducted, photomicrographs of each impact site were taken to assess the external damage to the tube since nearly all of these blunt impacts were not visible to the naked eye. The damage zones were dissected from this tube and cross sectioned through the impact site and mounted for polishing. A fluorescent dye penetrant and black light photomicroscopy were used to observe the extent of microcracking in these samples just as it was done for the tube sections hit by the "sharp" impactor.

## III. RESULTS

### A. Sharp Impacts

Table 1 summarizes the results obtained for the sharp tip impacts. The tips on hits No. 1 through 10 consisted of a $^{10}/_{24}$ steel bolt with varying degrees of sharpness. Sample photographic documentation of the sharpness is presented in appendix A. For hits 11 through 19, a conical indenter that came to a 2-mm diameter semispherical end (called a tup) was used. This represented

Table 1. Summary of results for sharp tipped impacts.

| Hit No. | Bolt Type | Impact Energy (J) | Maximum Load (N) | Visual Damage/Leak |
|---|---|---|---|---|
| 1 | No. $^{10}/_{32}$ unsharpened | 3.76 | 1,004 | Clearly visible circular indentation with cracks/heavy leak rate |
| 2 | No. $^{10}/_{32}$ unsharpened | 2.45 | 1,027 | Clearly visible circular indentation with cracks/heavy leak rate |
| 3 | Freshly sharpened | 2.45 | 992 | Complete penetration |
| 4 | Tip blunted by previous impact | 0.88 | 939 | Clearly visible point damage with split/heavy leak rate |
| 5 | Sharpened bolt slightly blunted | 0.87 | 579 | Clearly visible point damage with smaller split/heavy leak rate |
| 6 | Tip blunted by previous impact | 1.34 | 610 | Very deep damage with cracks/very heavy leak rate |
| 7 | Tip blunted by 2 previous impacts | 0.80 | 561 | Visible nick with small split/medium leak rate |
| 8 | Tip blunted by 3 previous impacts | 0.83 | 619 | Barely visible nick/no leak |
| 9 | Sharpened bold, blunted | 0.80 | 570 | Clearly visible nick/medium leak rate |
| 10 | Tip blunted by previous impact | 0.80 | 561 | Visible nick/no leak |
| 11 | 2-mm tup | 0.96 | 676 | Barely visible nick/small leak |
| 12 | 2-mm tup | 1.27 | 774 | Barely visible dent with small crack/medium leak rate |
| 13 | 2-mm tup | 1.56 | 819 | Visible dent with cracks/medium leak rate |
| 14 | 2-mm tup | 1.76 | 828 | Visible dent with large crack/heavy leak rate |
| 15 | 2-mm tup | 2.03 | 890 | Visible dent with long crack/heavy leak rate |
| 16 | 2-mm tup | 1.00 | 716 | Visible dent with cracks/medium leak rate |
| 17 | 2-mm tup | 1.00 | 716 | Visible dent with crack/medium leak rate |
| 18 | 2-mm tup | 0.81 | 681 | Barely visible dent with small split/medium leak rate |
| 19 | 2-mm tup | 0.75 | 708 | Barely visible dent with very small split/low leak rate |

a much less sharp tip than the machined bolts, thus dents began to form on the surface of the tube beginning with hit No. 11 rather than puncture type damage which occurred in hits No. 1 through 10. In order to represent the tube being impacted by a protruding bolt, the bolt was not machined for hits No. 1 and 2. All of the leak checks were done with up to 60 $lb/in^2$ gauge of gas pressure.

1. Surface Damage. The surface damage from the sharp impacts, beginning with impact No. 7, are given in appendix B. The impacts before hit No. 7 were all very visible including hit No. 3 which caused complete penetration.

On impact No. 7, the first hit that did not produce obvious external damage, the photomicrograph shows that a small crater has formed in the outer gel coat of the tube's surface. Two small cracks in the gel coat propagate from this crater. Specimen dissection, discussed in the next section, will show if any fiber damage has occurred. However, no fiber damage needs to occur for permeability to be present, only a leak path through the matrix resin is needed.

Hit No. 8 is an example of damage that did not cause detectable leakage, yet was visible under microscopic examination. While damage such as this may not cause detectable leakage of argon gas using a soap based leak detector solution, hydrogen permeation may still occur at high rates.

Also of interest is hit No. 10 that caused a visible nick in the surface, yet did not cause a detectable leak. The cross-sectional examination results, given in the next section, will show why this is. Hit No. 11 shows far less surface damage than hit No. 10, yet hit No. 11 leaked while hit No. 10 did not. Thus, surface damage alone is not a good indicator of whether or not an impact event will cause leakage. One explanation for this is that hit No. 11 was performed with a 2-mm diameter striker which was relatively blunt compared to the sharpened bolt strikers. The impact energy due to a blunt hit is distributed over a wider area and less contact stresses occur, thus the energy is dissipated as matrix cracking through the entire thickness of the tubes instead of the localized puncture that may not go through the thickness. This seems to be the case since all impacts with the 2-mm diameter striker caused leaks even though the impact energies were lowered to the lowest level used with the sharpened bolts (~0.8 J).

2. Cross-Sectional Examination. Cross-sectional photomicrographs taken under a black light source are given in appendix C. These photographs provide valuable data as to the mechanisms taking place that cause leak paths to develop due to foreign object impact. The matrix cracking shows up as the highlighted lines in the photographs. Any areas that absorbed the dye penetrant indicates cracks or microvoids since the penetrant was washed off the surface of the specimens leaving only dye that had worked its way into cracks or voids.

From the cross section of hit No. 7, it can be seen that no fiber breakage is present, but extensive matrix cracking exists. This was found to be typical of all of the impacts except Nos. 1, 2, and 3, which demonstrated obvious fiber breakage visible from the surface. The majority of the lengths of these cracks run between plies of carbon/epoxy as is typical of impact delamination damage. The leak paths form when these lines of delamination are joined by transverse cracks that bridge between layers. Some of these cracks can be seen on the photomicrograph of hit No. 7. Since the entire volume of impact damage cannot be represented by a cross-sectional photograph, a complete leak path may not be visible on any one plane perpendicular to the specimen. Thus, the density of cracks on the plane in the photomicrograph must be used to assess the likelihood of a leak path forming through the entire tube wall thickness. For example, the cross-sectional photograph of hit

No. 8 seems quite similar to that of hit No. 7, yet No. 7 leaked while No. 8 did not. These two photographs represent the borderline impact level at which leakage begins to occur.

The surface damage can be seen in the cross-sectional photograph of hit No. 9. The typical conical region of damage observed in impact damaged composites can be seen in this, and most other, photomicrographs. This type of damage consists of heavy matrix damage below the impact site, with delaminations spreading out further away from this point as the specimen gets deeper.

As mentioned in the previous section, hit No. 10 sustained a visible surface nick yet did not leak. The photomicrograph of this specimen helps confirm the theory that the punctured area near the surface absorbed most of the incident impact energy, leaving little energy to form delaminations and matrix cracking deeper in the specimen. The photomicrograph of hit No. 11, which was similar to hit No. 10 only with a more blunt striker, shows that not as much surface damage was inflicted upon the specimen, allowing the impact energy to be dissipated into the entire thickness of the tube wall as delaminations and matrix cracking.

## B. Blunt Impacts

Table 2 summarizes the results of the blunt impacts. These impacts consisted of striking the tube with a 0.5-inch diameter semispherically ended rod (called a tup). This type of impactor was chosen so representations of tool drops and dropping the tube on a hard surface could be obtained. The damage was much less notable than for the sharp tipped impacts. Under ×8 magnification, some form of surface indication of the impact could usually be observed. Impacts that produced no visible damage (to the unaided eye) could form detectable leaks in some cases. Under microscopic observation, it was usually found that these specimens incurred some form of cracking in the outer gel coat of the composite tube.

Table 2. Summary of results for blunt impacts.

| Hit No. | Impact Energy (J) | Maximum Load (N) | Visible damage/Leak |
|---|---|---|---|
| 1 | 2.66 | 850 | Crack visible/leak easily detectable at 5 $lb/in^2$ gauge |
| 2 | 1.52 | 890 | Very slight split on surface/leak easily detectable at 5 $lb/in^2$ gauge |
| 3 | 0.60 | 663 | No visible damage/no leak at 60 $lb/in^2$ gauge |
| 4 | 0.83 | 716 | No visible damage/leak at 25 $lb/in^2$ gauge |
| 5 | 0.88 | 846 | No visible damage/no leak at 60 $lb/in^2$ gauge |
| 6 | 0.87 | 859 | Surface cracking visible under microscope/leak at 7 $lb/in^2$ gauge |
| 7 | 0.88 | 912 | No visible damage/leak at 20 $lb/in^2$ gauge |
| 8 | 0.83 | 841 | No visible damage/no leak at 60 $lb/in^2$ gauge |
| 9 | 0.84 | 903 | No visible damage/no leak at 60 $lb/in^2$ gauge |
| 10 | 0.88 | 921 | No visible damage/no leak at 60 $lb/in^2$ gauge |
| 11 | 0.88 | 854 | No visible damage/no leak at 60 $lb/in^2$ gauge |
| 12 | 0.88 | 957 | No visible damage/no leak at 60 $lb/in^2$ gauge |
| 13 | 1.03 | No data | Very small surface crack/leak at 15 $lb/in^2$ gauge |
| 14 | 1.03 | 908 | No visible damage/no leak at 60 $lb/in^2$ gauge |
| 15 | 1.06 | 899 | Small split visible under microscope/leak at 10 $lb/in^2$ gauge |
| 16 | 1.06 | 810 | Very small split visible under microscope/leak at 10 $lb/in^2$ gauge |

1. Surface Damage. Surface photomicrographs of the damage that caused leaks are given in appendix D. All of the photographs show matrix gel coat cracking in the region near the impact site with no localized damage present. This is due to the large diameter striker being used, which helps

to spread the impact energy over a larger area, reducing localized damage. Note that on hits No. 4 and 6, the cracking was contained within the seam of the gel coat caused by the outer clamshell mold used in the processing of the part. These areas are resin rich, and the cracks can propagate much more easily in these areas than in those outside the seam which contain fibers closer to the surface. This indicates that impacts that occur on the "seam" of the tube may be much more difficult to visually inspect, thus care must be taken for these impacts.

2. Cross-Sectional Examination. Cross-sectional photomicrographs of the impacted areas that caused leaks are given in appendix E. Extensive delaminations and matrix cracking are evident on specimens No. 1 and 2 as might have been expected due to the high leak rates observed. Specimens No. 4 and 6, which had surface damage confined to the "seam" area of the tube, show typical delaminations and matrix cracking, indicating that subsurface damage is not effected by the visible damage being restricted to the "seam" area. Specimen No. 15 shows the typical conical type damage mentioned in the previous section on sharp impacts.

## IV. CONCLUSIONS

From this study, it was found that nonvisible impact damage could form leaks that were detectable using small pressures of argon gas and a soap-bubble leak detection solution. The leak paths form as a result of matrix delamination and microcracking through the thickness of the tube wall. Cross-sectional examination revealed that the cracks tend to propagate mostly between plies (delaminations) and will provide the through-the-thickness leak path by propagating from one ply to another.

Sharp tipped objects pose a severe threat to the formation of leaks, however, blunt objects can impact the tube, producing nonvisible damage, yet still form a leak path which can result in a dangerous situation.

If a detectable leak does occur due to a foreign object impact event, then cracking of the outer gel coat of the tube is associated with it even though in many cases this cracking can only be seen under microscopic examination.

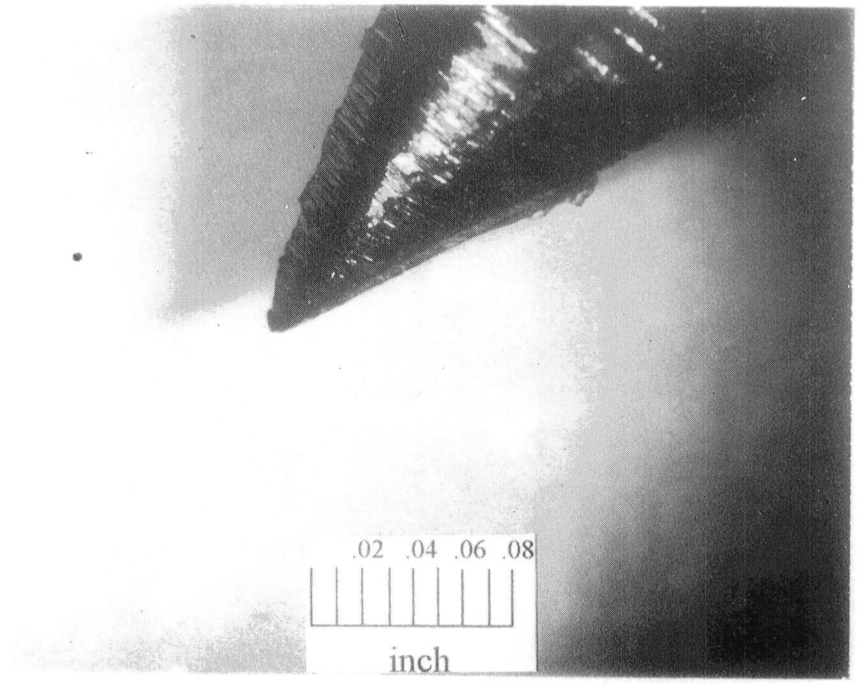
Thus if leakage due to foreign object impact damage is to be avoided, the composite hardware must be handled with extreme caution.

## V. REFERENCE

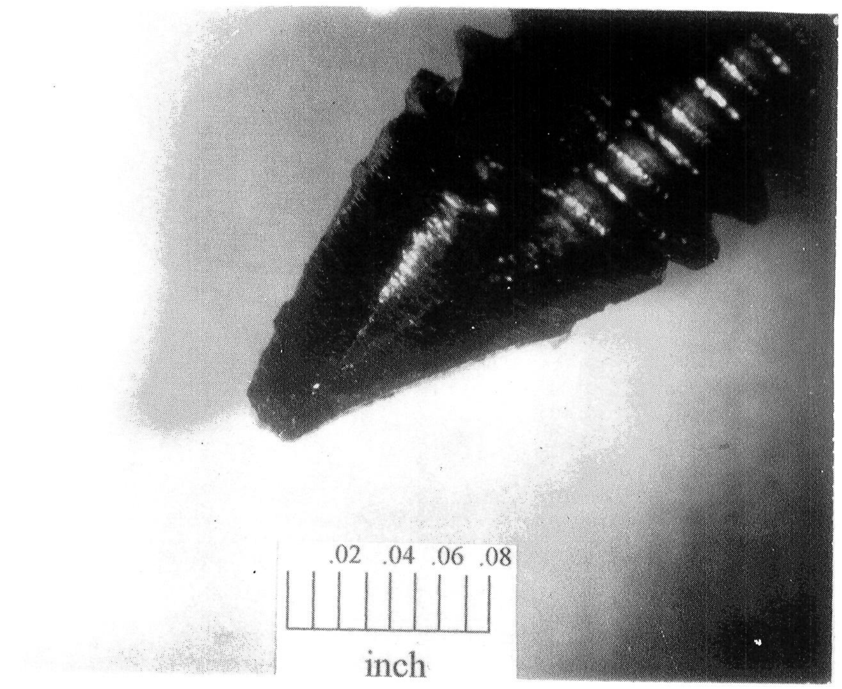
1. Nettles, A.T.: "Permeability Testing of Composite Material and Adhesive Bonds for the DC-XA Composite Feedline Program." NASA TM 108483, March 1995.

# APPENDIX A

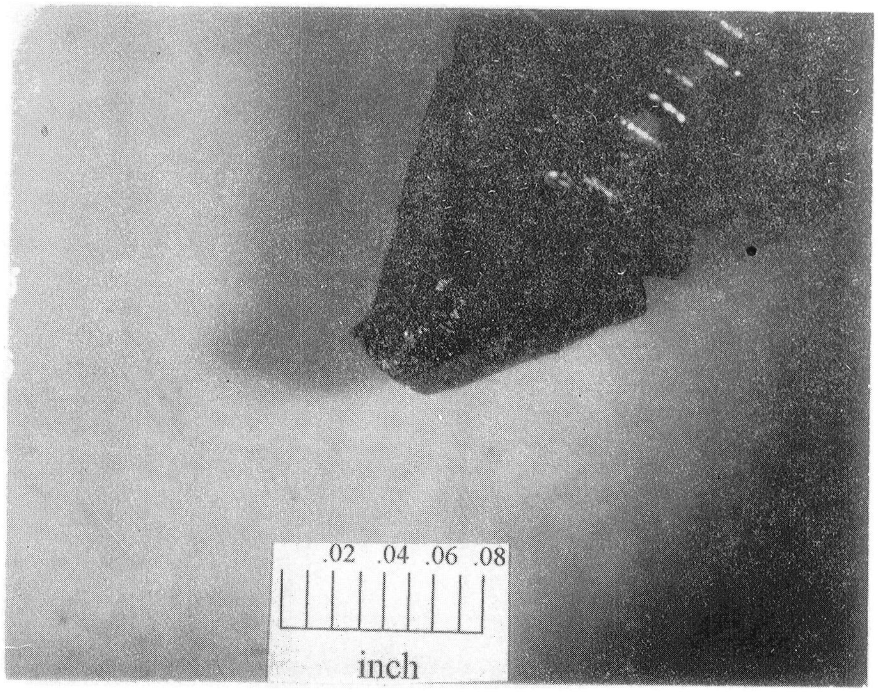
## Photographs of Impactors Used for Sharp Type Impacts



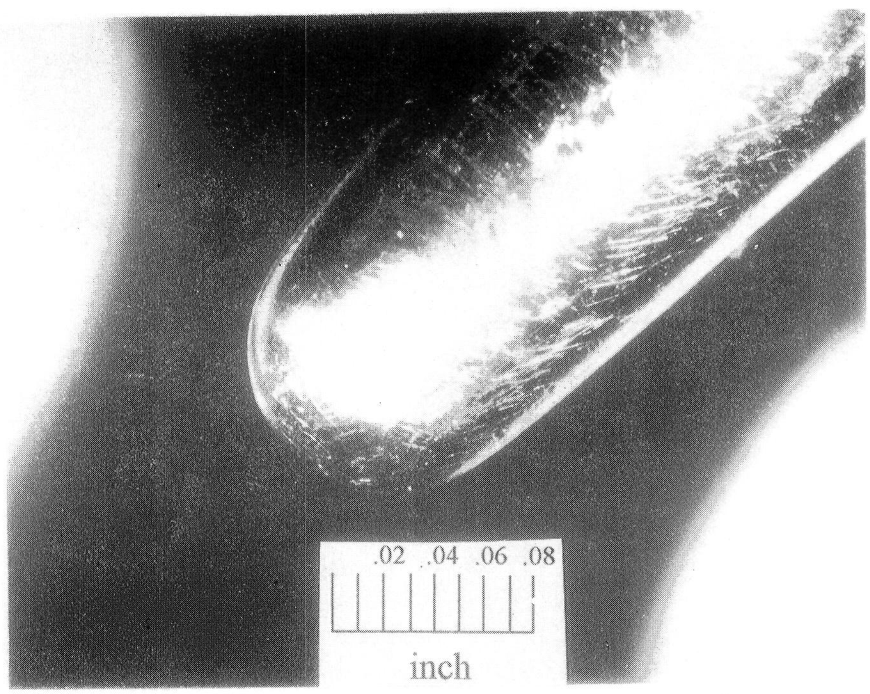

Freshly sharpened bolt used for impact 3.




Bolt used for impacts 3 and 4.



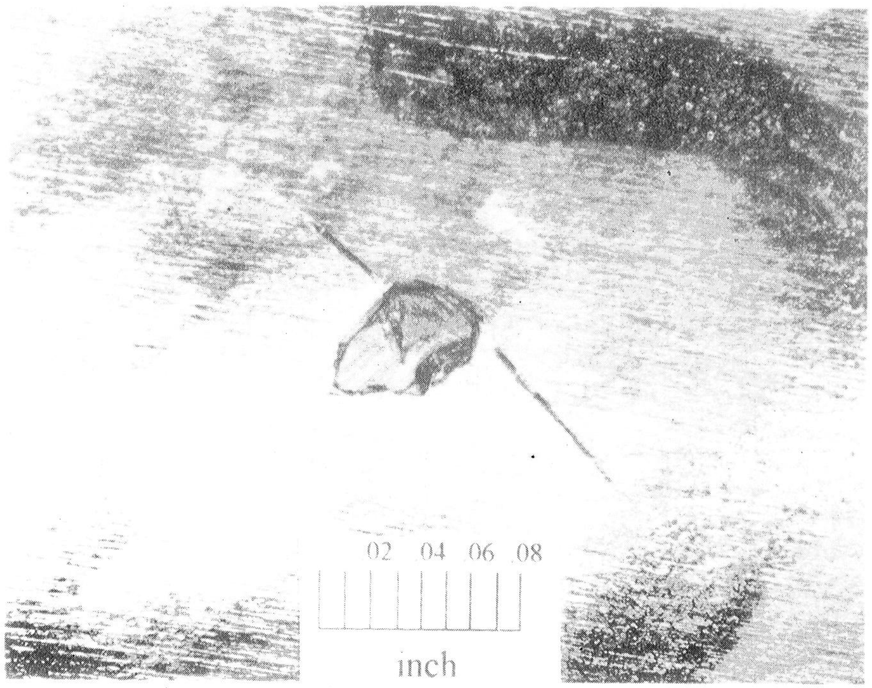

Bolt used for impact 9.




Tup used for impacts Nos. 11 through 19.

## APPENDIX B

## Surface Damage Due to Sharp Type Impacts

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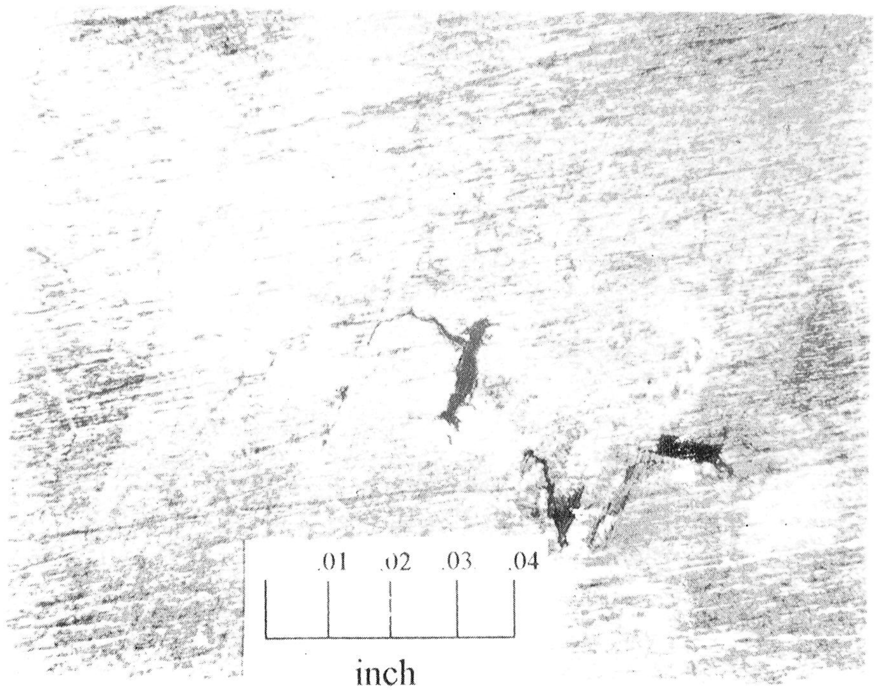


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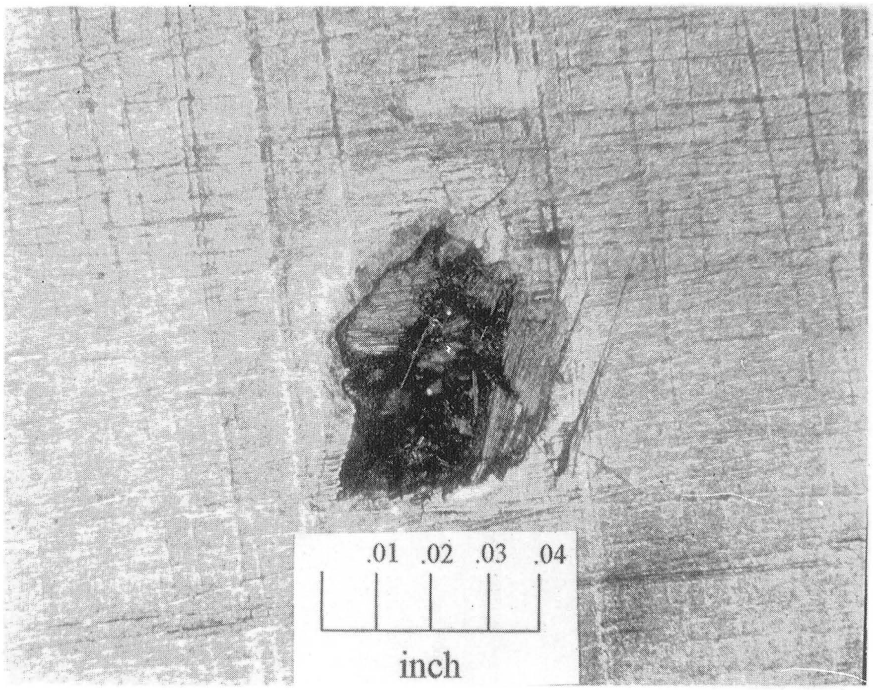


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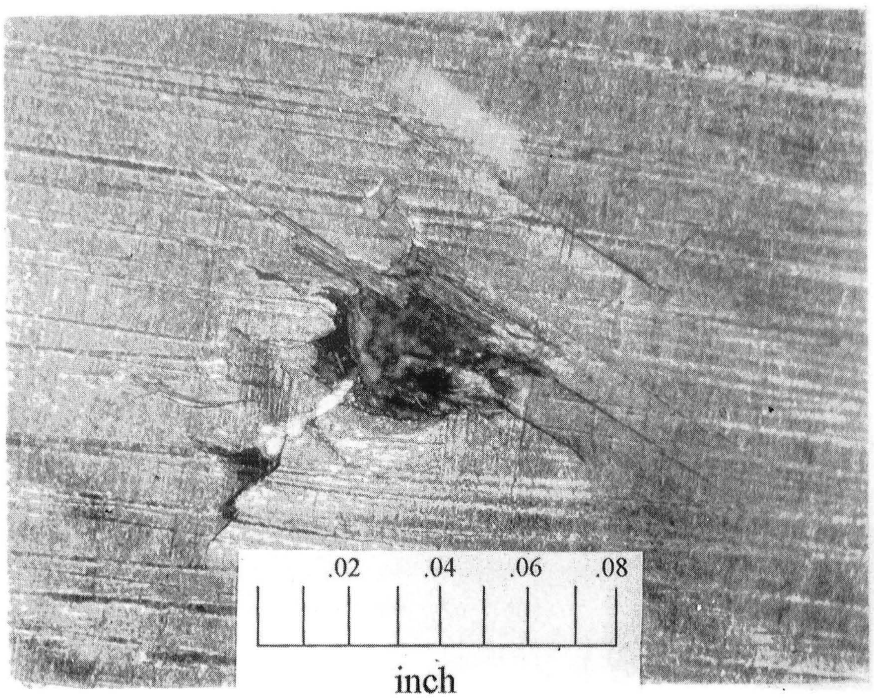


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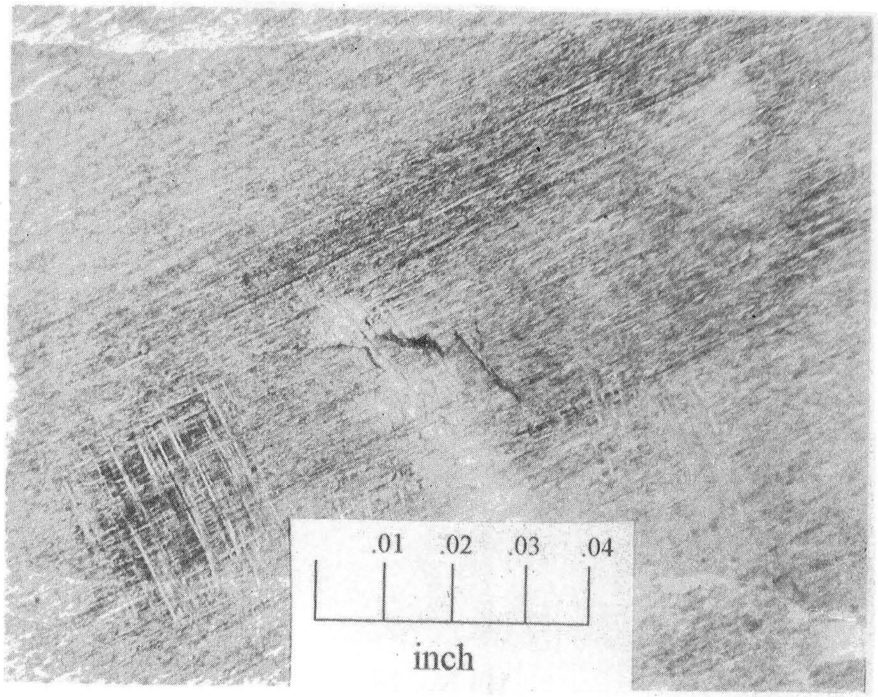


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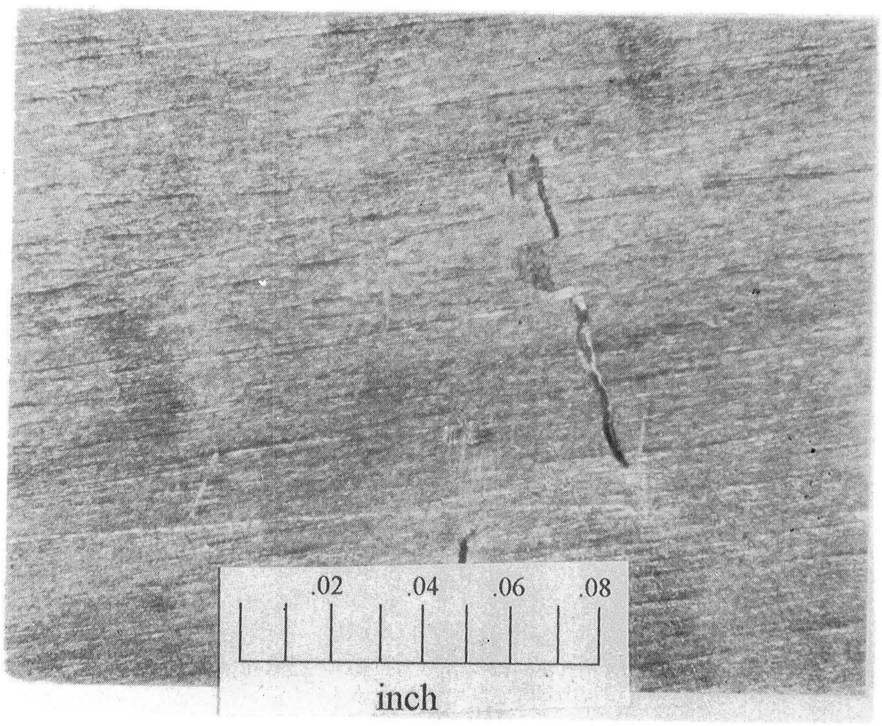


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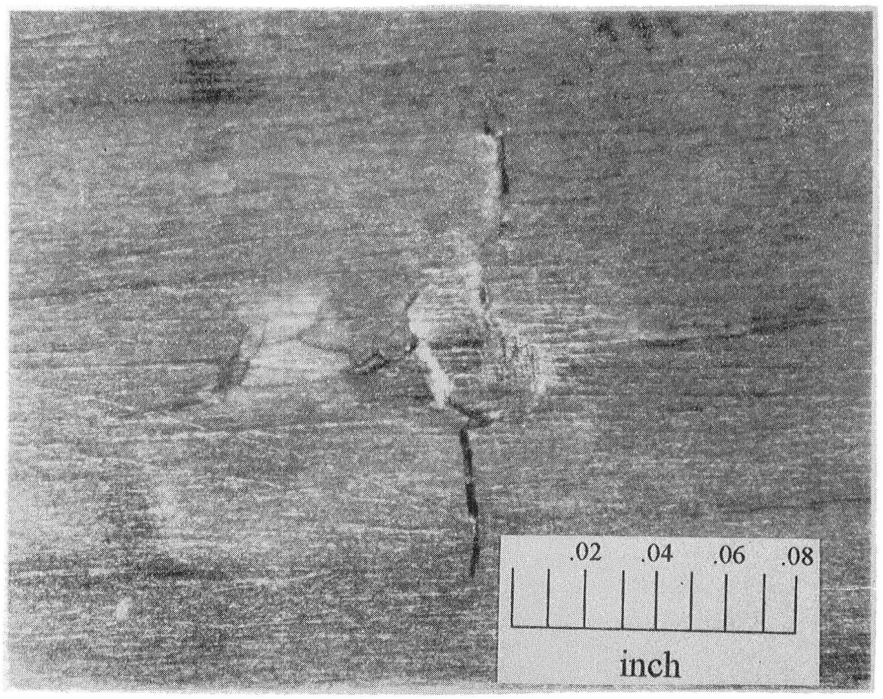


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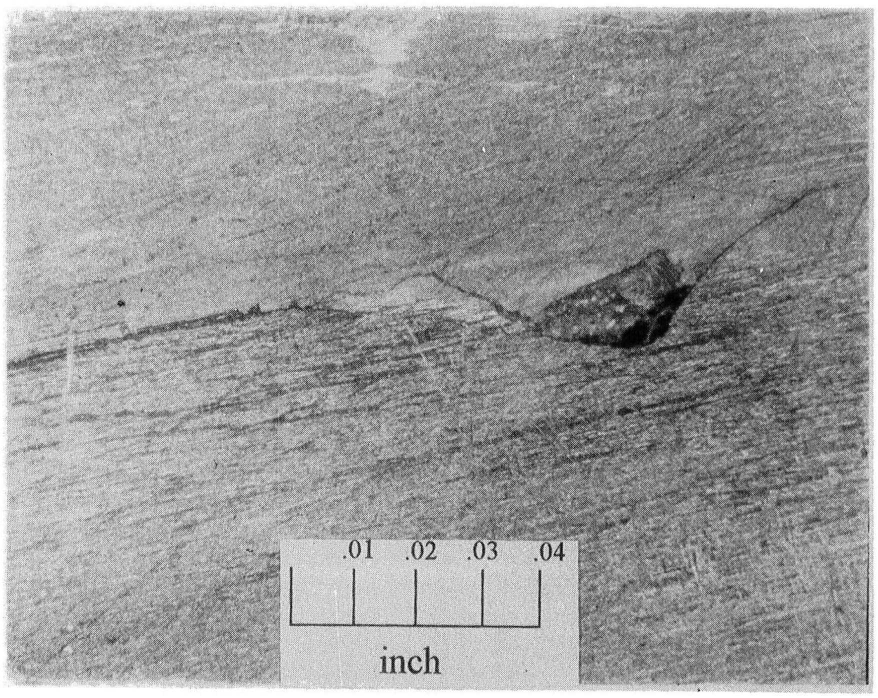


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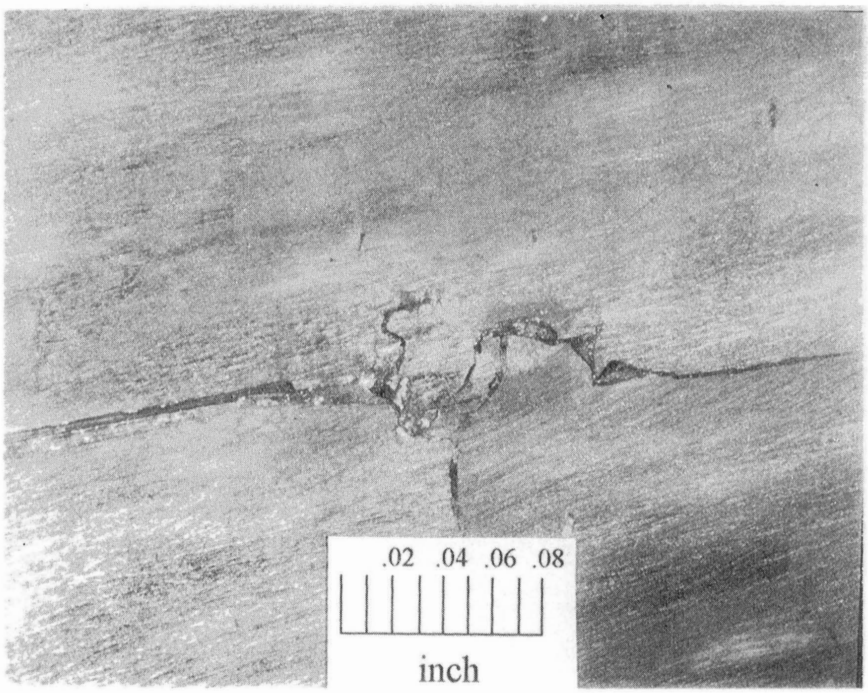


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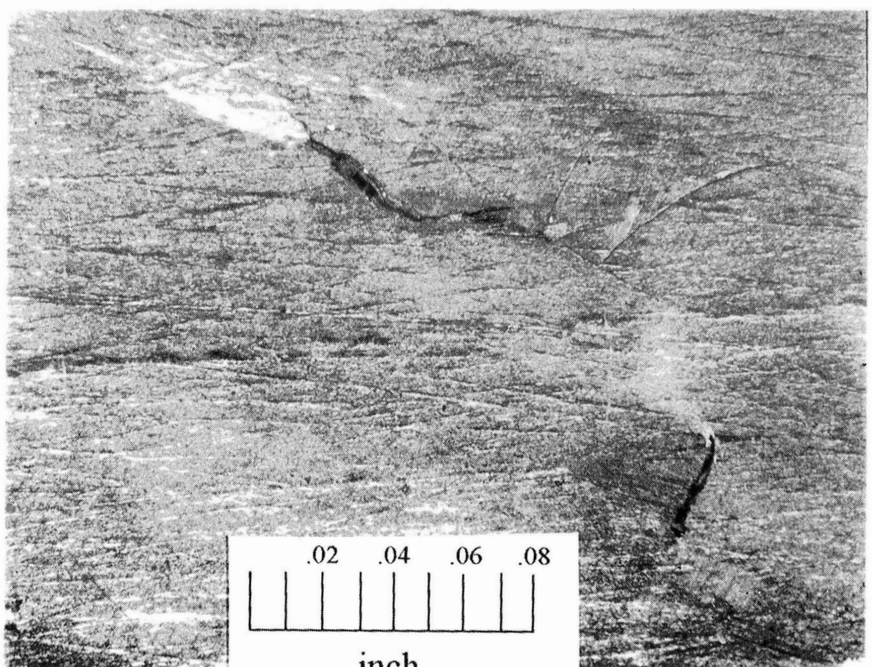


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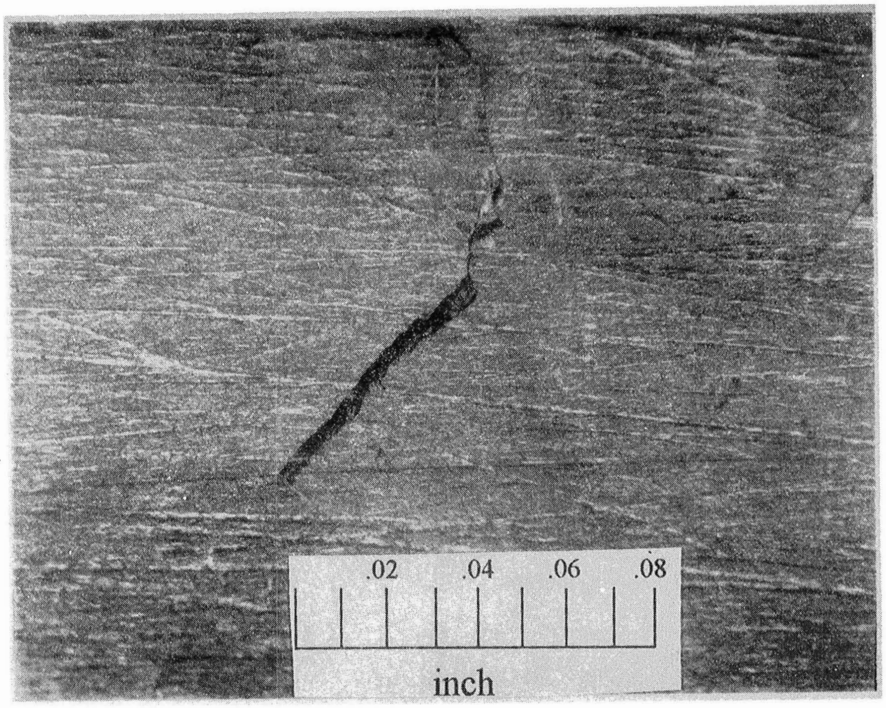


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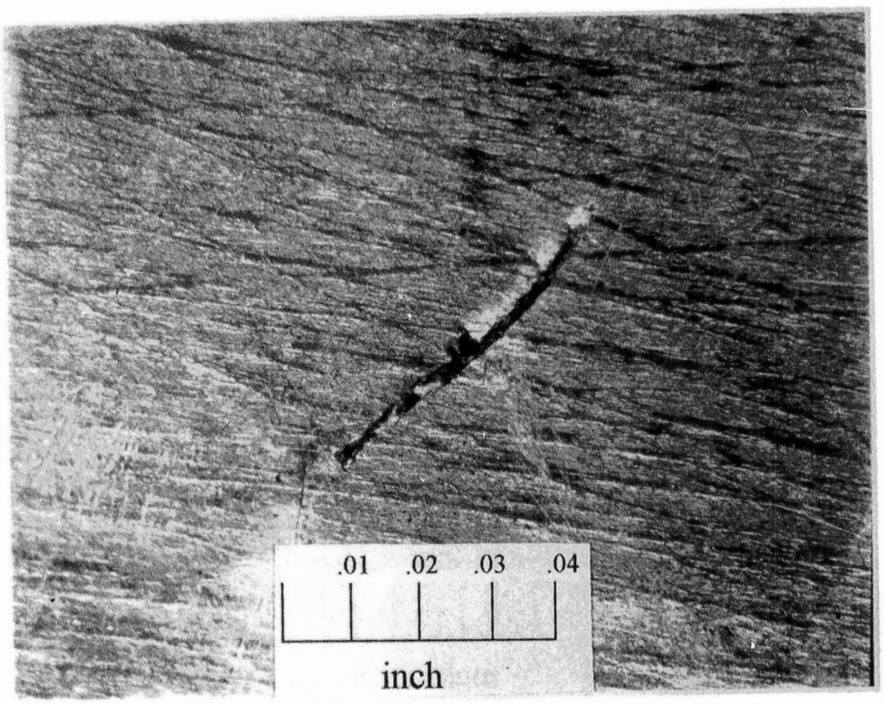


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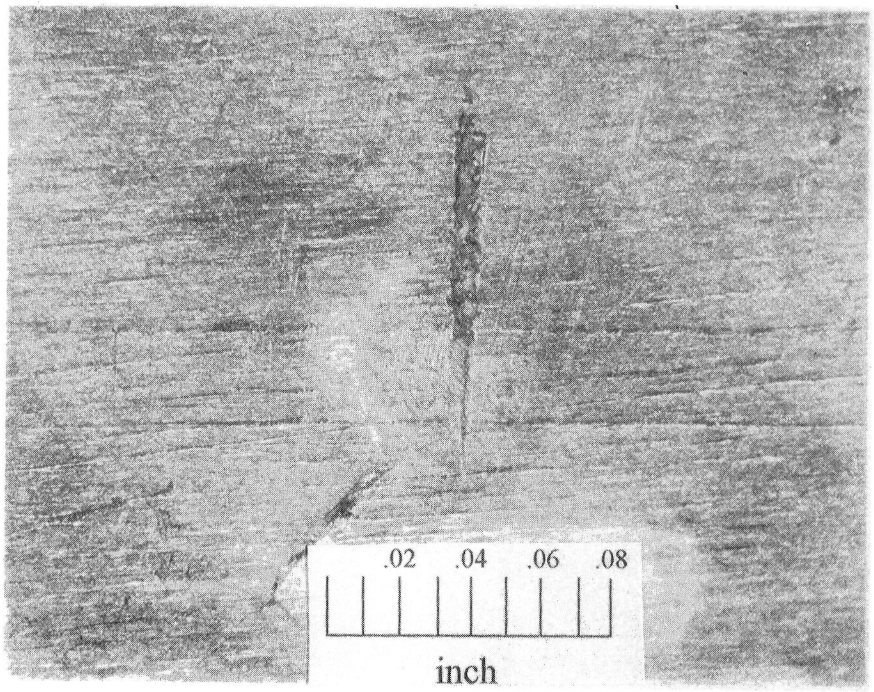

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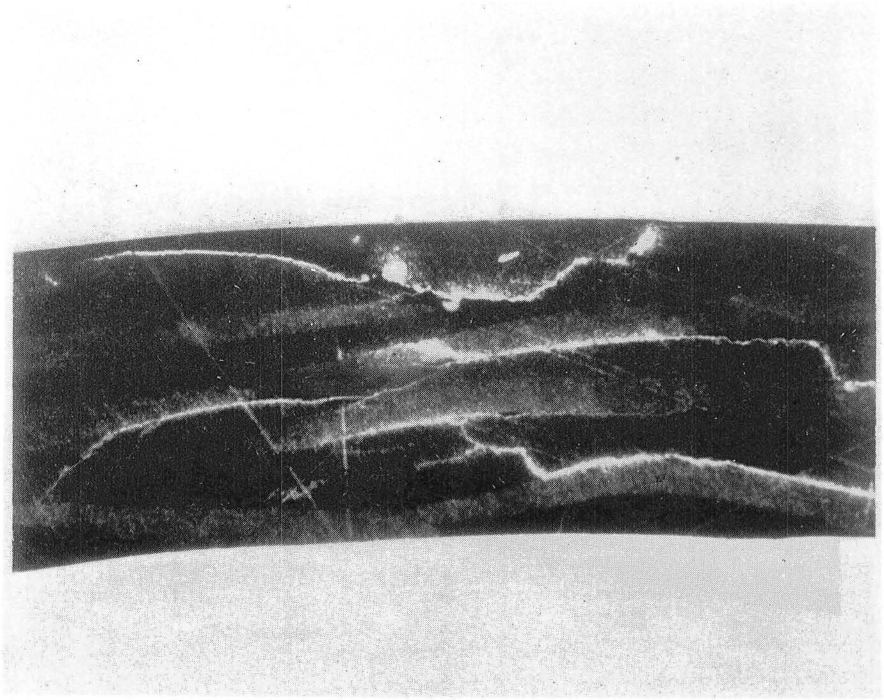
# APPENDIX C

## Cross-Sectional Photomicrographs of Sharp Hits



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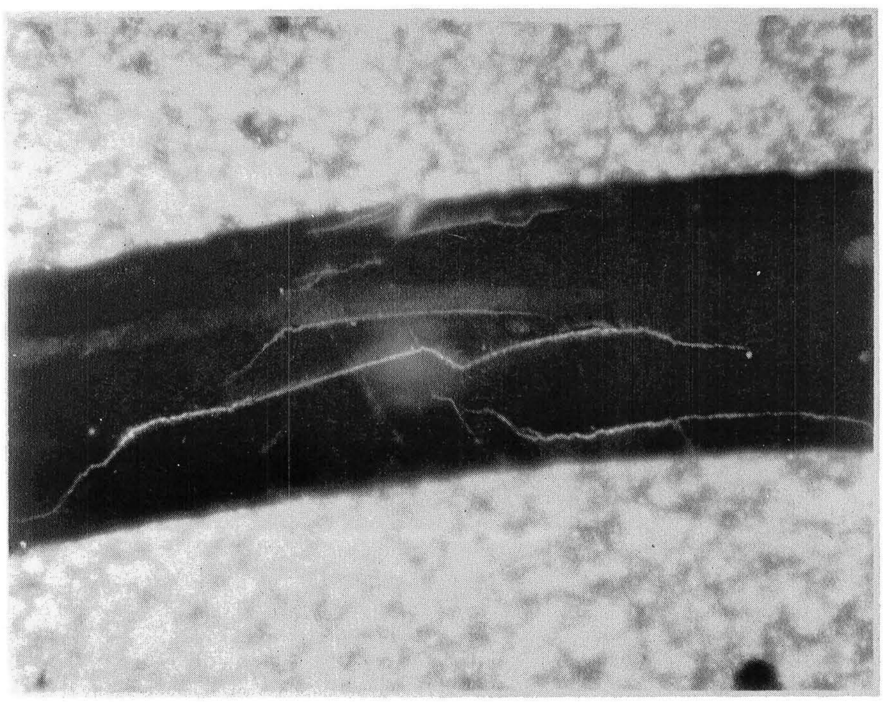

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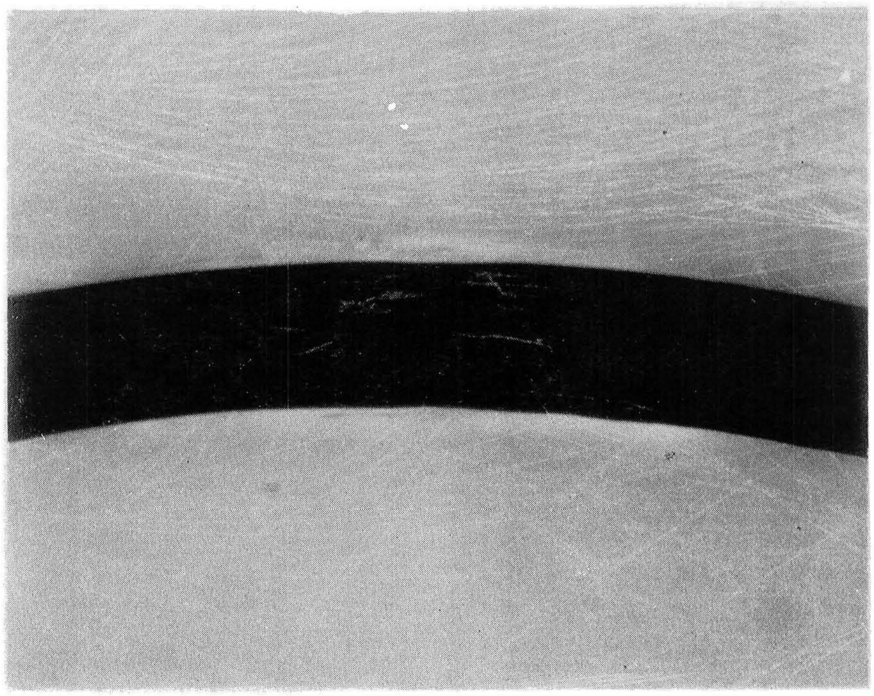

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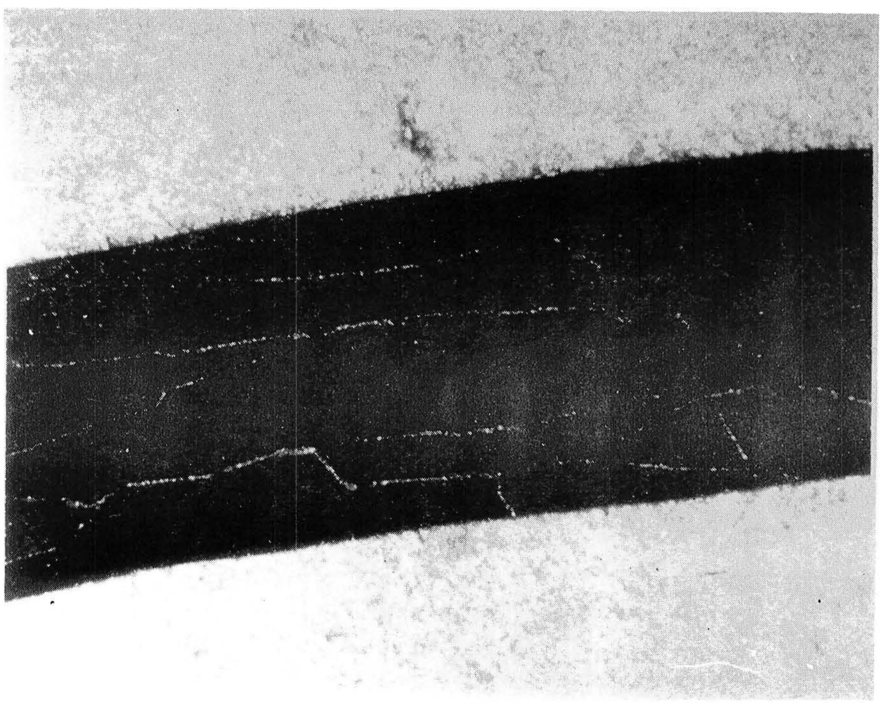

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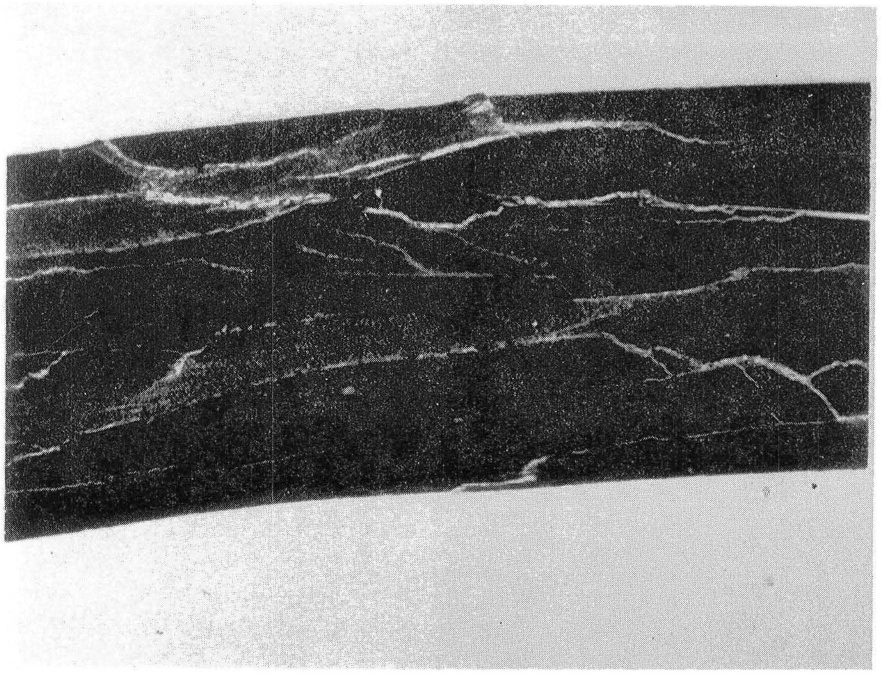

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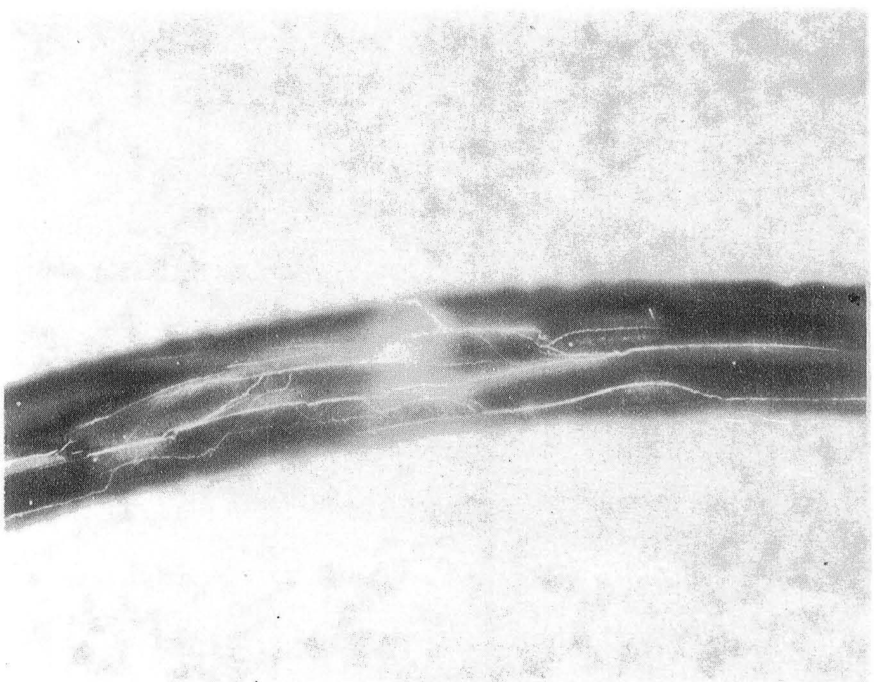

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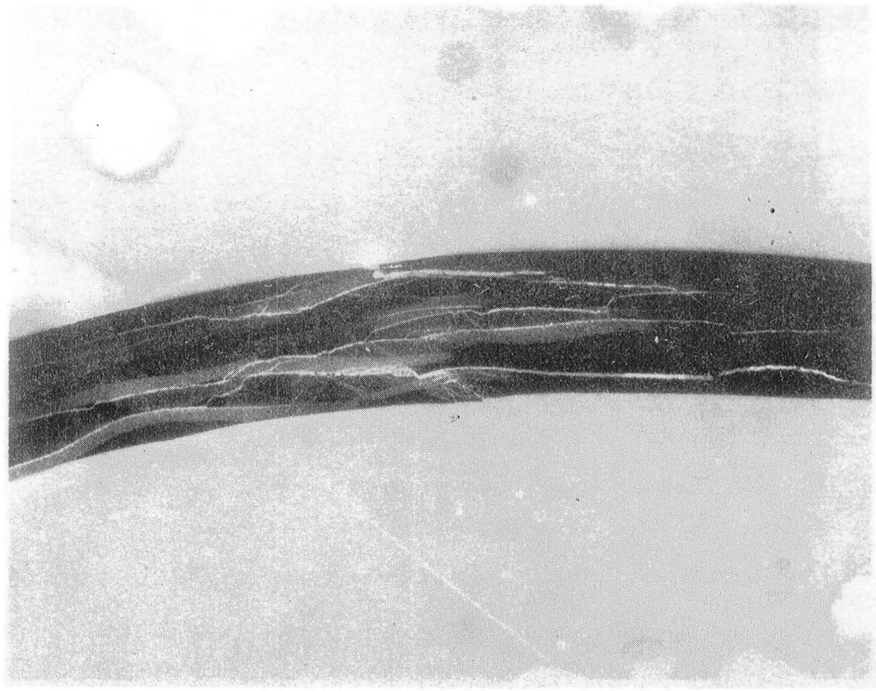

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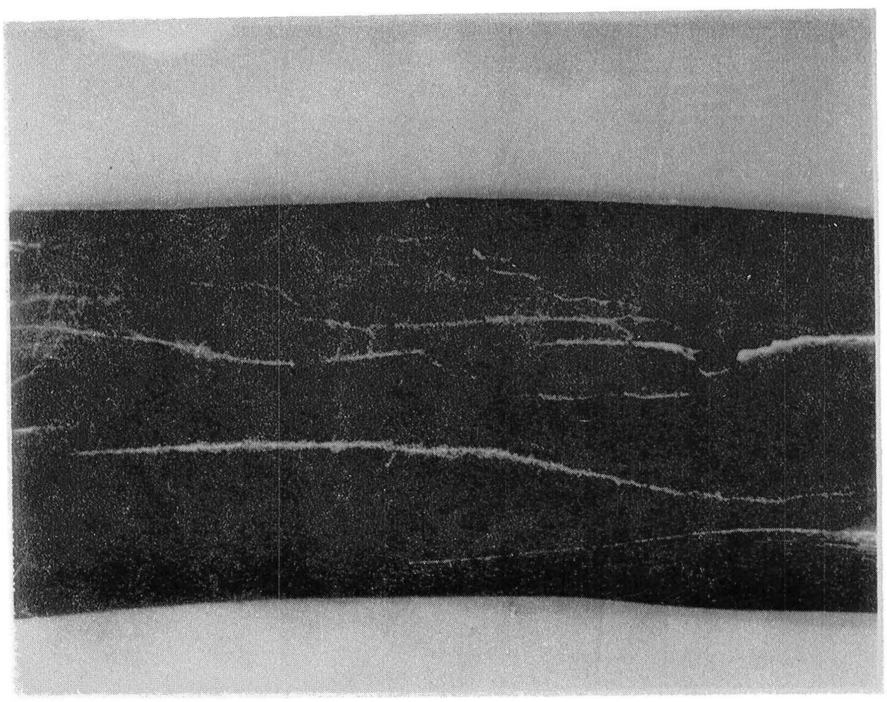

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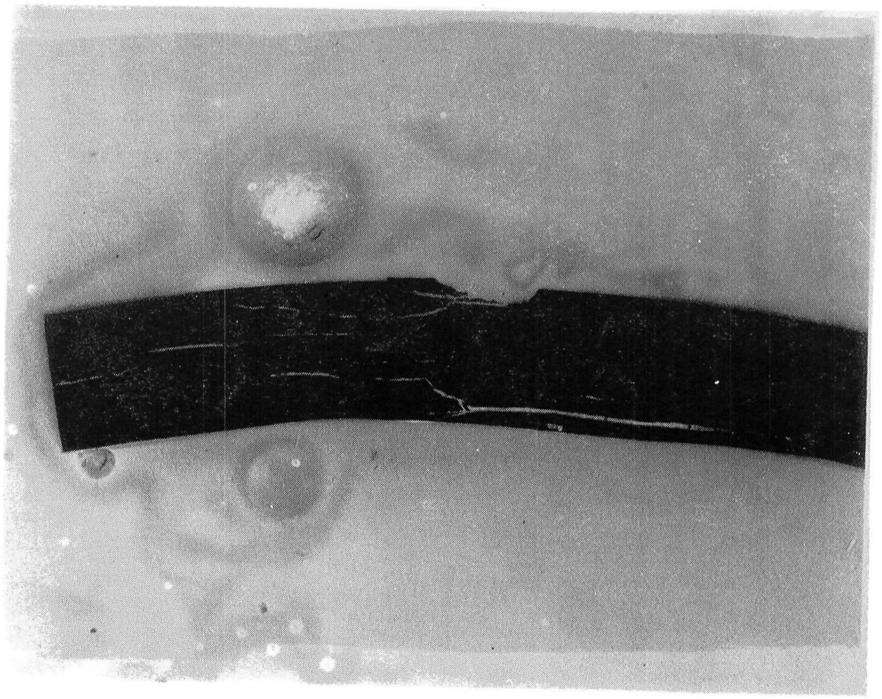

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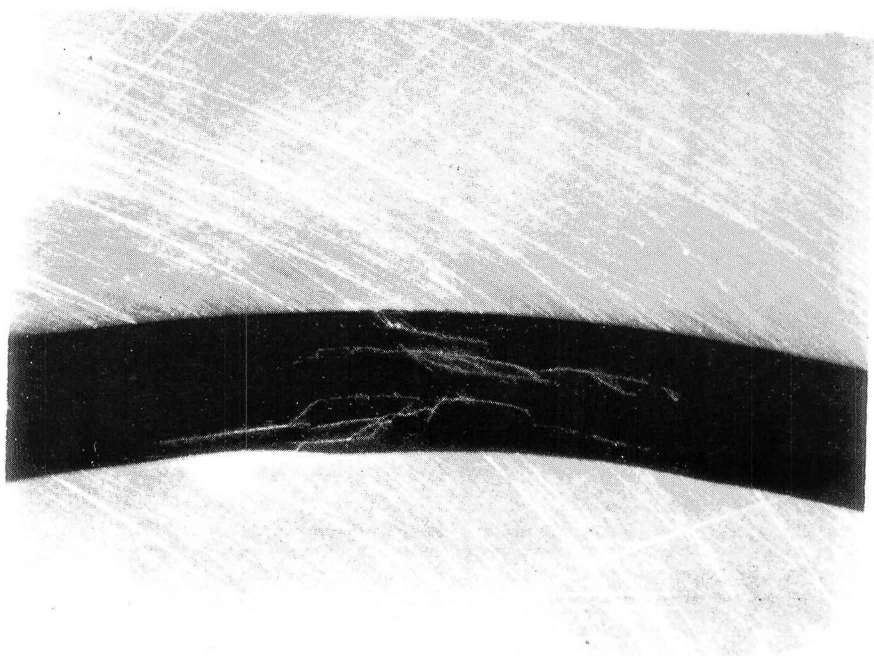

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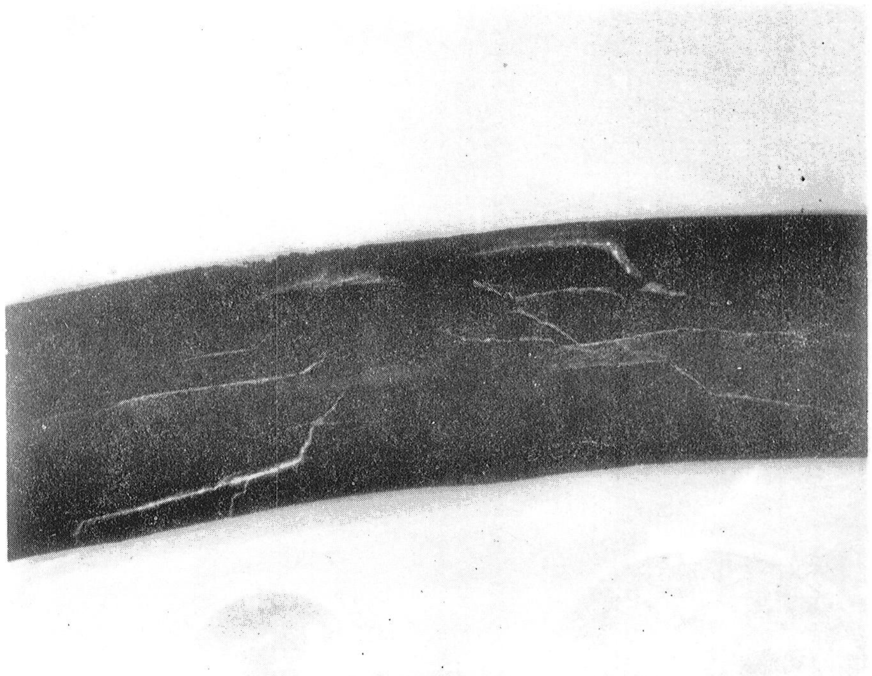

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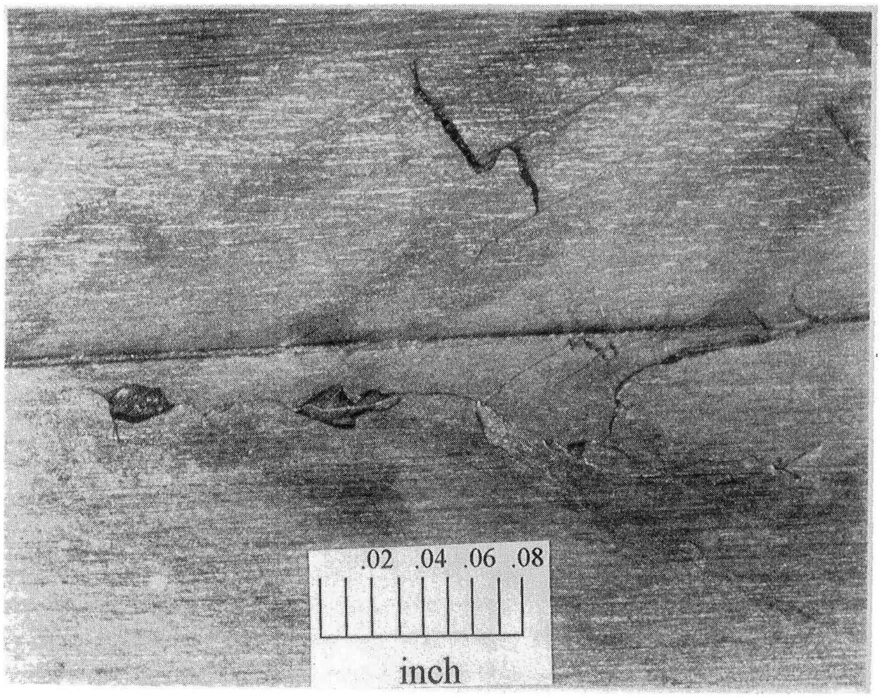
## APPENDIX D

## Surface Photographs of Damage From Blunt Hits

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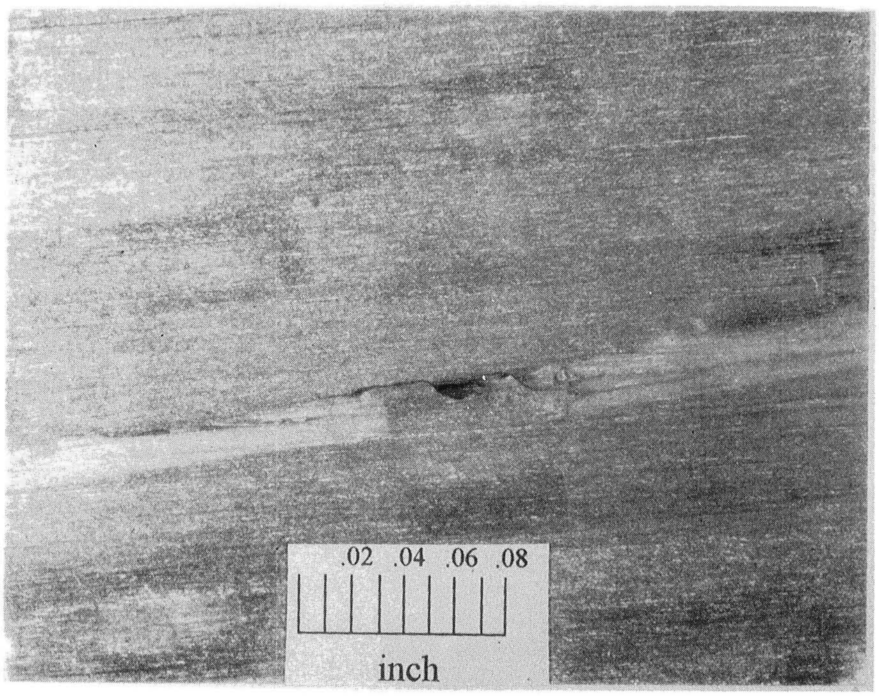


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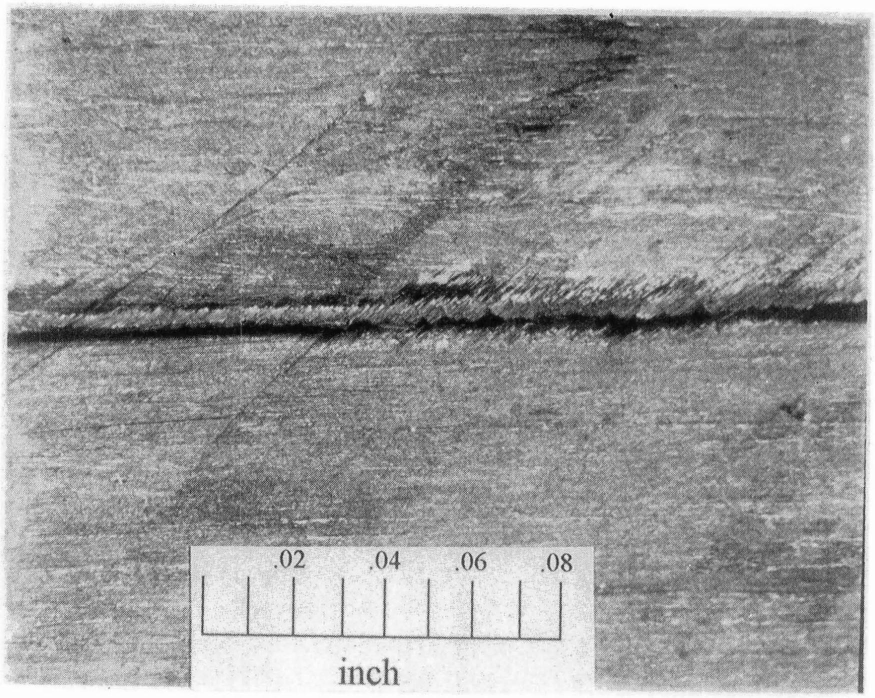


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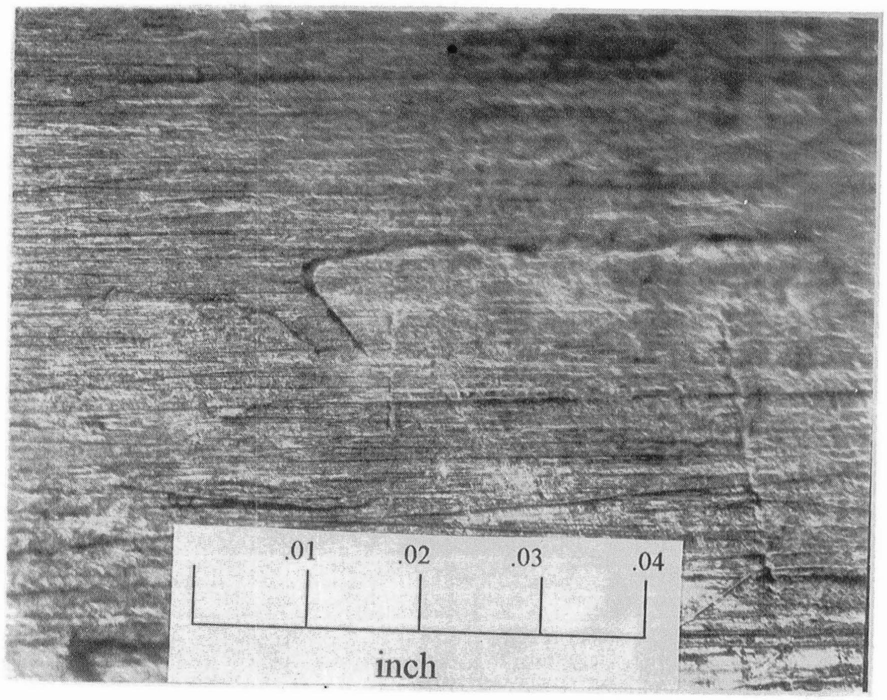


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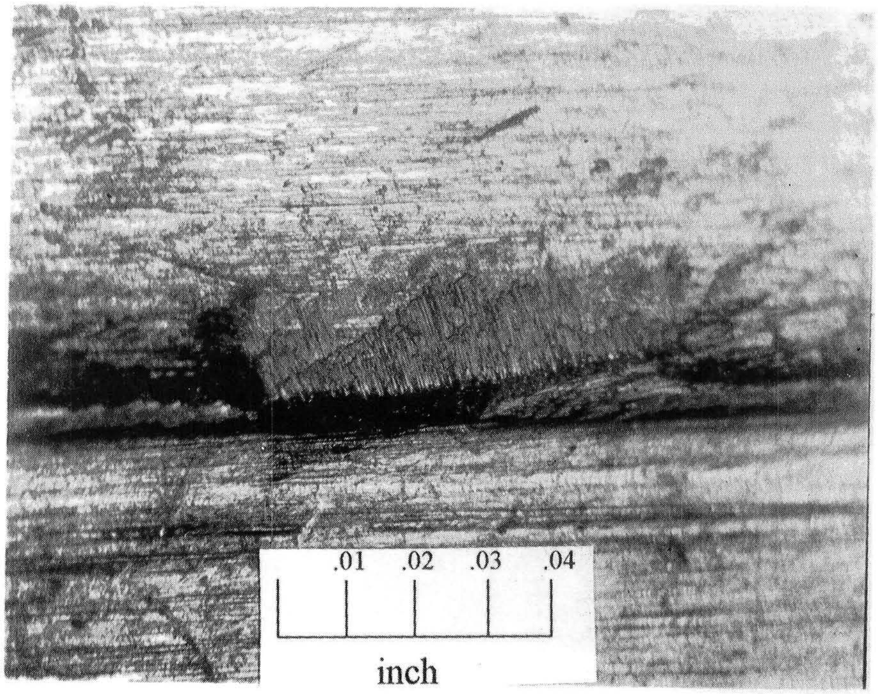


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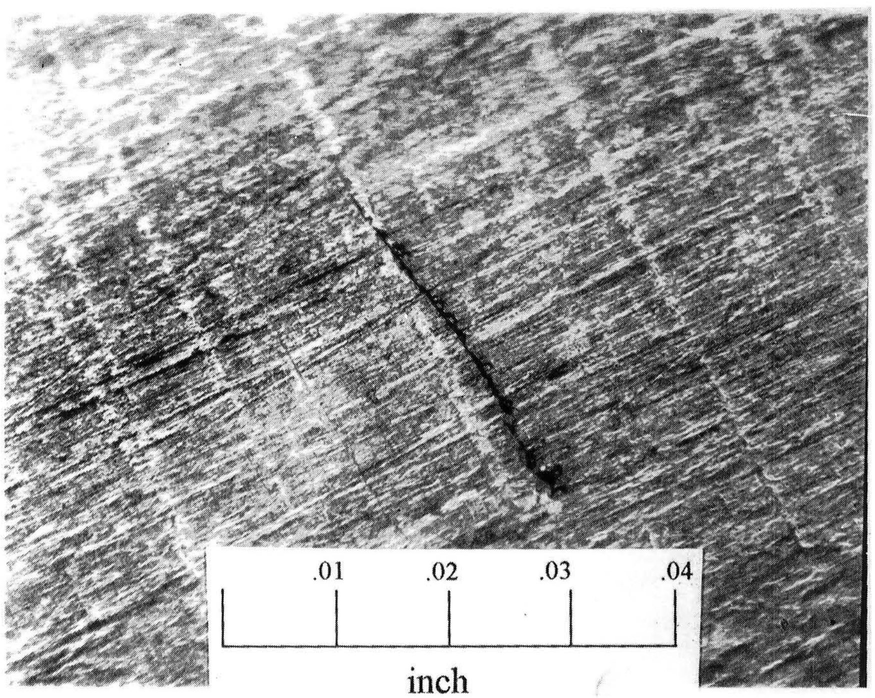


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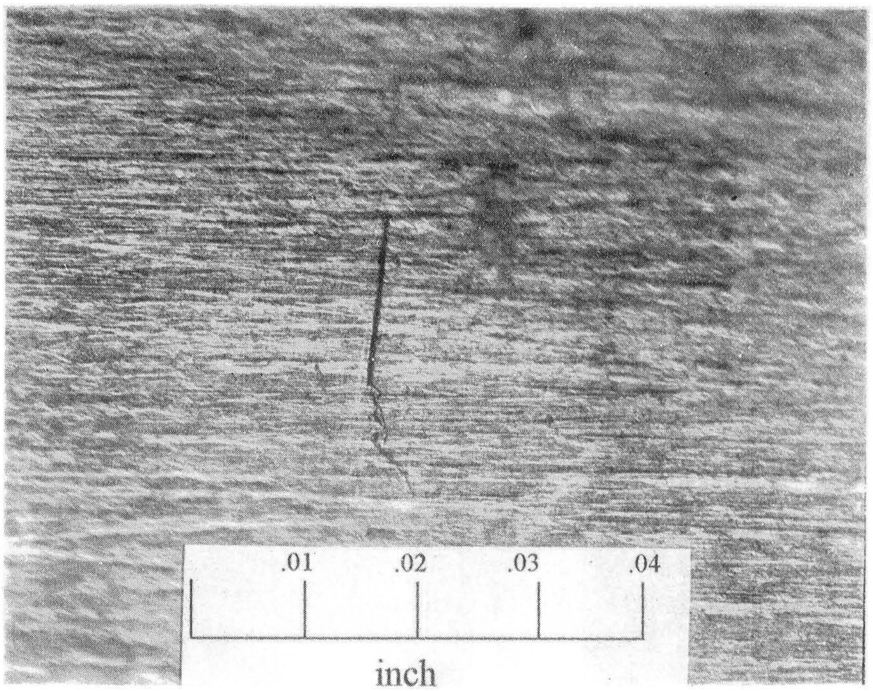

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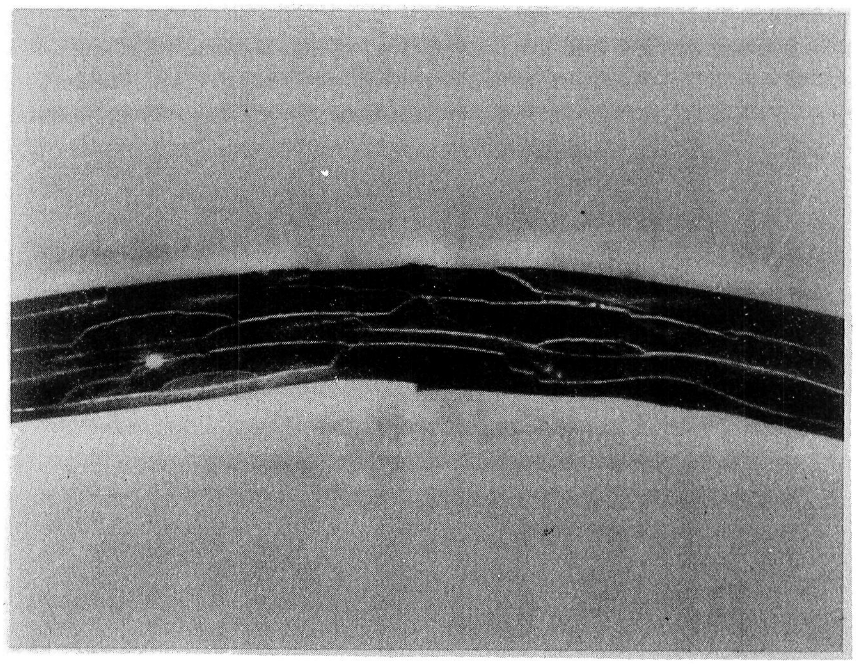
# APPENDIX E

## Cross-Sectional Photomicrographs of Blunt Hits



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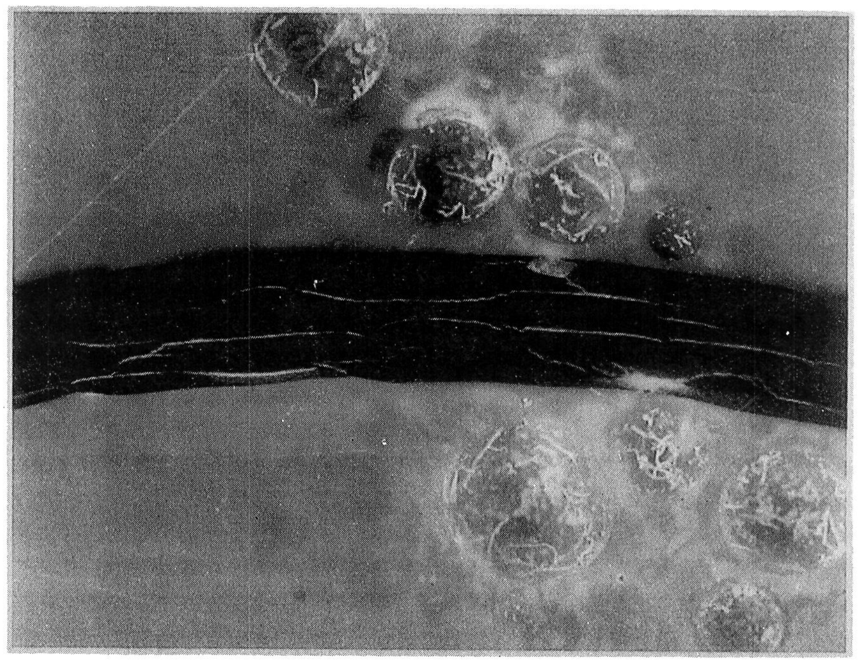

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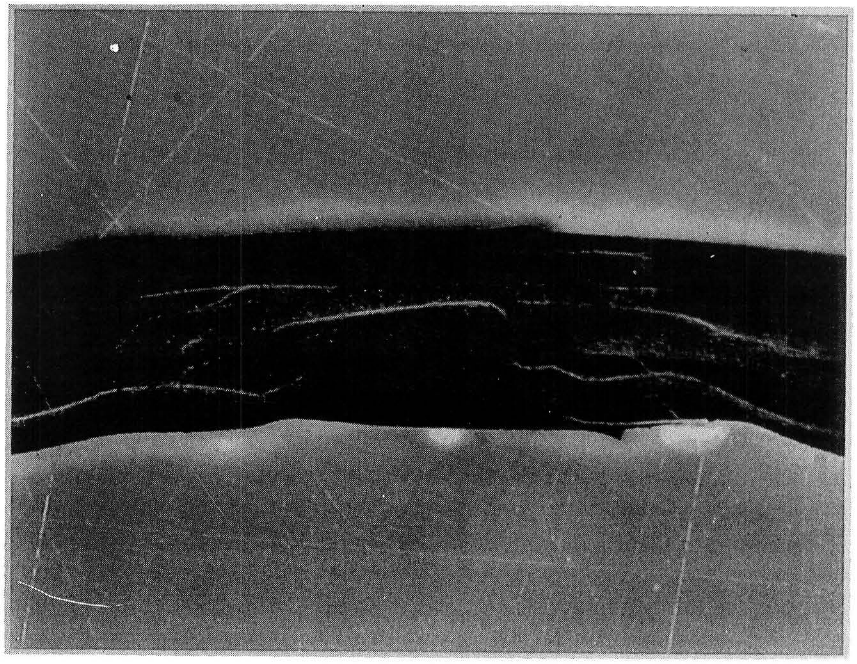

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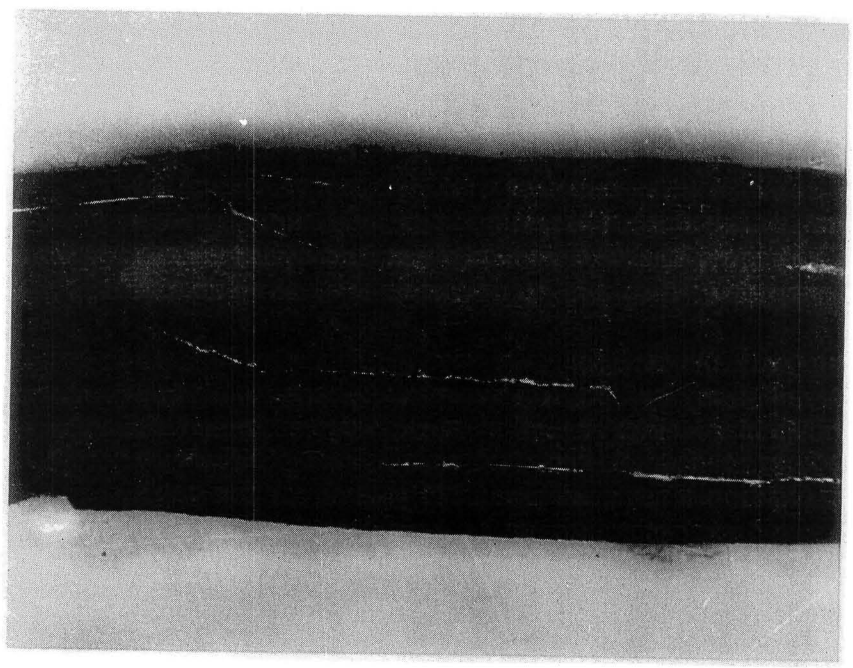

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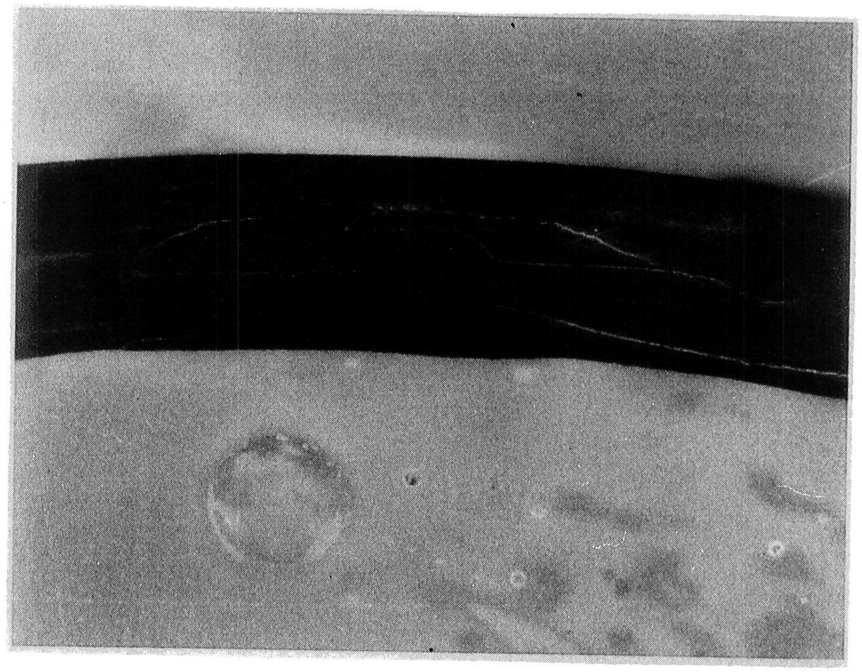

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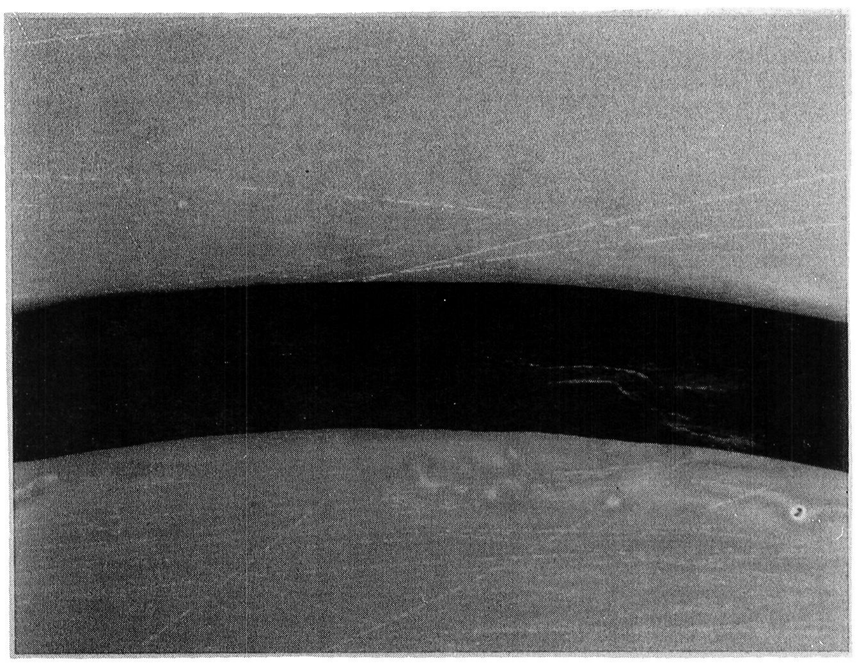

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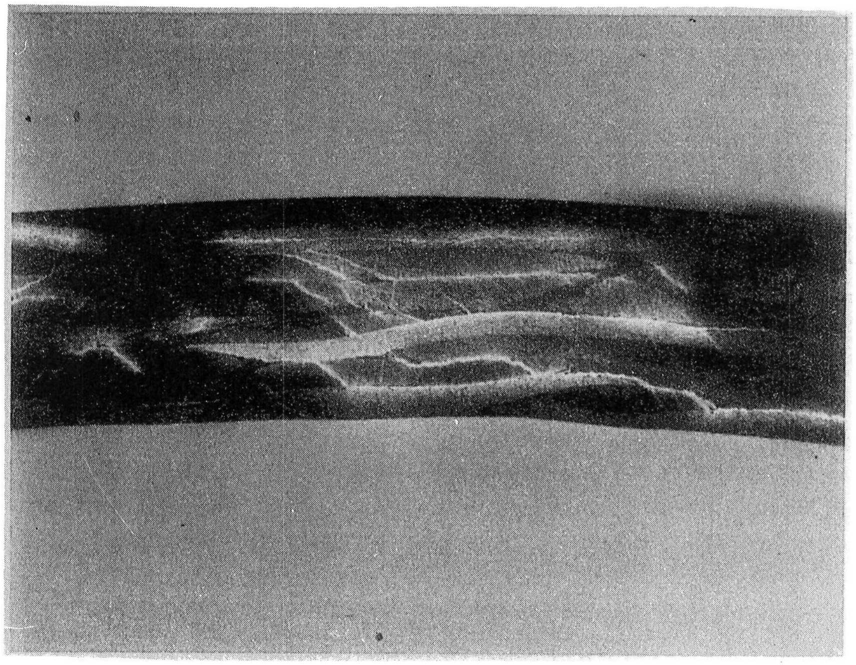

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Low-velocity impacts were inflicted upon two elbow sections of carbon/epoxy feedline that are to be a part of the Delta Clipper-XA flight vehicle. A soap-based liquid leak detector solution was used to inspect the impact sites for leaks of pressurized gas that was pumped into the tube. Visual surface damage was noted and recorded for each impact site. After impact testing of each of the two sections of tubes was completed, the damage zones were dissected from the tube and cross sectioned through the impact site. These specimens were polished after potting them in epoxy and were examined for microcracking using a fluorescent dye penetrant technique. The results showed that nonvisible damage could cause microcracking, thereby resulting in leaks through the tube wall.

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