NATIONAL TRANSPORTATION SAFETY BOARD
Bureau of Technology
Washington, D. C.

August 17, 1987

Materials Laboratory
Report No. 87-89

# METALLURGIST'S FACTUAL REPORT

## A. ACCIDENT

| | | |
|---|---|---|
| Place | : | Marlin, Texas |
| Date | : | March 30, 1987 |
| Vehicle | : | Piper PA-28-181, N8191U |
| NTSB No. | : | FTW 87-F-A087 |
| Investigator | : | Warren V. Wandel (FTW-ASI) |

## B. COMPONENTS EXAMINED

1. Left wing, root area of fractured main wing spar assembly with attached portions of upper and lower skins and fuselage carry through structure.
2. Two addition sections of upper skins with cracks.
3. Aft spar attachment fitting, two pieces.
4. Right wing, fractured lower main spar cap, inboard fracture section and fasteners.

## C. SUMMARY


The left wing main spar and associated hardware had separated chordwise along the wing root with fractures through the upper and lower spar caps, spar gusset webs and wing skins. Additional cracks were present in the upper wing skins outboard of the main spar separation.

Two regions of fatigue progression were found in the forward flange of the left wing lower spar cap. The fatigue had initiated at two locations on the lower surface of the spar cap in the vicinity of the forward most outboard, spar to carry through, bolt hole.

The fatigue had propagated completely through the forward flange and partially into the aft flange and spar web. The remaining lower spar cap fracture area was overstress fractured.

The upper spar cap fracture was entirely overstress consistent with an upward bending of the wing tip relative to the fuselage.

A small (0.07 x 0.03 inch) region of fatigue cracking was located on the forward gusset web in the area of the forward attachment bolt hole.

The fatigue had initiated on the lower web surface in the area of the forward bolt hole. The remaining fracture surface and fracture of the aft gusset were typical of overstress separations.

The upper skins were cracked in two areas. The forward skin was cracked between rivets at the inboard edge just forward of the main spar. The aft wing skin was cracked at three rivets that attached the aft skin to the second outboard rib.

The forward and aft skin cracks were opened and each displayed fatigue characteristics. The fatigue in each crack had initiated on the upper surface of the skin under the manufactured heads of associated rivets.

The fracture of the right wing lower spar cap was through the outboard attachment bolt holes and determined to be overstress in nature. No evidence of fatigue cracking was detected.

The edges of bolt holes in the left wing aft fuselage attachment brackets were deformed consistent with the presence of a bolt.

## D. DETAILS OF EXAMINATION

### Left Wing Main Spar

The left wing main spar assembly pieces are shown in figure 1. The spar had separated through the upper and lower spar caps and through the forward and aft sheet metal gusset webs. The locations of these fractures are denoted by arrows in figure 1.

The lower spar cap was fractured through the furthest outboard, spar to fuselage carry through, attachment holes. The inboard spar cap end was received with a portion of the fuselage carry through structure containing the attachment bolts in-place.

Initial examination of the lower spar cap fracture faces detected the fracture characteristics of fatigue cracks emanating from two areas near the outboard attach hole in the forward flange of the spar cap. Figure 2 displays photographs of both the inboard and outboard spar fracture faces, with the fatigue areas denoted by white brackets.

The ten lower spar fasteners were removed and the bolt loosening torques were measured. The measured removal torques are listed in Table A. During disassembly of the inboard spar cap section a fretting pattern was noted on the carry through structure outboard of the spar fatigue area. Removal of the spar section from the carry through revealed a prominent demarcation line between the fretted and unfretted surface, as denoted by arrows "D" in figure 3. This demarcation line corresponded to the location and the profile of the fatigue zone in the spar cap. A matching fret pattern was found on the lower surface of the outboard spar piece, white bracket in figure 4. Inspection of the lower surface of the inboard spar section immediately inboard of the fatigue zone did not detect any evidence of fretting damage, see figure 5.

With the inboard spar section removed from carry through structure, both fracture faces were cleaned with a mild detergent solution in water and repeated applications and stripping of replication tape. The cleaned fatigue zone of the outboard fracture half is shown in figure 4. Magnified examination of the spar fracture established that the fatigue region was composed of two independent fatigue planes that were slightly offset to each other in the spanwise direction. Both fatigue planes had intersected the forward outboard attachment bolt hole near the outboard edge of the hole. Figure 5 illustrates the orientation and relationship of the two fatigue planes and the bolt hole.

Further examination identified a single point of fatigue initiation on each fatigue plane. Both fatigue origins were on the lower surface of the spar cap slightly away from the bolt hole. The fatigue origins are denoted by arrows "O" in figures 4 and 5. The origin on the forward (most inboard) fatigue plane was just inboard of the outboard edge of the bolt hole and about 0.14 inch forward of the spanwise centerline of the bolt hole. The aft (most outboard) fatigue plane origin was offset about 0.06 inch outboard of the hole edge and the forward fatigue plane and approximately 0.07 inch aft of the bolt hole centerline.

Fatigue growth in the forward fatigue plane was generally upward and forward and entirely penetrated the portion of the spar flange between the bolt hole and the forward edge of the spar cap. The aft fatigue plane extended upward through the flange thickness and aft, terminating at a position slightly aft of the spar web as denoted by the white line in figure 4.

Detailed magnified examination of the aft fatigue plane revealed two distinct topographies. The topography in the initial region (closer to the origin) consisted entirely of fatigue beach marks. This initial region was about 0.5 inch long and transitioned into a region which contained alternating bands of fatigue beach marks and overstress features. Near the beginning of this second region, the bands of fatigue markings dominated the intervening overstress bands. However, near the end of alternating mode zone the relative sizes of the fatigue and overstress bands had reversed with the overstress bands becoming the dominant feature. Beyond the fatigue terminus the entire fracture surface of the spar cap displayed features typical of an overstress separation.

The forward flange (containing the two fatigue planes) of the outboard fracture spar cap piece was saw cut from the remainder and prepared for scanning electron microscope (SEM) viewing. SEM examination confirmed the initial mode of fracture as fatigue by revealing striations consistent with fatigue cracking. The fatigue striations emanated from a single location for each fatigue plane on the lower spar cap surface also confirming the previous visual observations. The two fatigue origin areas, arrows "O" are shown in the SEM macrographs of figure 6.

During SEM examination, X-ray energy dispersive analysis (XEDA) spectra were acquired. These spectra were consistent with a 2024 aluminum alloy.

A fatigue striation count was undertaken along the centroid line of the fatigue propagation directions on the aft fatigue plane. Fatigue striation spacing, expressed as striations per inch (S/I), was determined at three positions along the centroid of propagation. These spacings were then linearly integrated over the distance to the previous measurement position. Adding the three integrated spacing measurements, in this manner, results in a conservative estimate of the total fatigue striations for a given length of propagation. For the aft fatigue plane, a minimum of 30,265 fatigue striations were present in the initial 0.49 inch of measured fatigue propagation. The propagation centroid line, fatigue origin, and three measurement points are located on the SEM montage in figure 7. The measurement data at the three points are listed in Table B.

Metallography

A metallographic cross section was cut through the lower spar cap approximately 1.0 inch outboard of the fracture location. When polished and etched with Keller's Reagent, this section displayed a macrostructure typical of an aluminum extrusion with a large grained layer, 0.045 to 0.060 inch thick adjacent to the spar surfaces and surrounding a smaller grained core. A cross section cut and prepared from the upper spar cap exhibited a similar macrostructure.

Additional metallographic specimens were prepared from the inboard portions of the left and right wing lower spar caps for microstructure examination. The microstructures shown in figure 8 are from the forward flanges of the spar caps approximately 1.25 inches inboard of the respective fractures. Again, these specimens exhibited a microstructure typical of an aluminum alloy extrusion. Further, the microstructures appeared to be consistent with the specified material and temper, 2024-T3511.

A microsection was also prepared through the left wing lower spar cap aft outboard bolt hole at the fracture plane. This section revealed a layer of plastic deformation adjacent to the bolt hole surface, as denoted by brackets "P" as in figure 9.

Upper Spar Cap

The upper spar cap was fractured through the outboard attachment bolt holes. Optical inspection of the fracture faces revealed features typical of an overstress separation. Deformation of the spar cap at the fracture was consistent with bending loads as if the left wing tip moved upward with respect to the fuselage.

Spar Specifications and Manufacture

The following wing spar specifications and manufacturing processes were relayed during telephone conversations with engineering representatives of Piper Aircraft. The spar was an extrusion supplied by Aluminum Company of America (Alcoa), die number 93500. The spar material was specified as 2024-T3511 aluminum alloy per Federal Specification QQ-A-200/3. This specification requires a minimum tensile strength of 60,000 psi in the direction of extrusion . The 9th Edition of ASM Metals Handbook Vol 2, indicates that a typical tensile strength for 2024-T351 would be 68,000 psi for sheet material with a typical hardness of 120 Brinell (BHN, 500 kg, 10 mm). From a Wilson mechanical instrument conversion chart number 60 120 BHN approximately corresponds to a 75 HRB level. The Metals Handbook also indicates that 2024-351 material would have a typical electrical conductivity of 30 % International Annealed Copper Standard (IACS).

After receipt of the extrusion, Piper Aircraft cold bends a 7 degree dihedral angle into the inboard end of the spar, straightens the extrusion and fluorescent penetrant inspects the spar. Several machining steps, including drilling the inboard attachment holes, are then performed prior to final assembly.

Hardness

Several series of hardness measurements were made on the left wing lower spar cap. Initially, a series of hardnesses in the Rockwell "B" scale (HRB) were made across the center of a transverse (chordwise) cross section of the spar cap located about 1 inch outboard of the fracture. These impressions ranged from 76.5 to 79.0 HRB and averaged 77.7 HRB. Several more tests were made directly on the flange surface at the same location using HRB and lighter loads of the 30T superficial scale. The HRB readings averaged 79.9 and ranged from 79.5 to 82 HRB. The three superficial values were 71 to 69.5 and 62.5 on the 30T scale that converted to 81, 79 and 69 HRB.

Microhardness measurements using a Knoop (HK) indenter were also performed on mounted and polished sections through the forward flanges of the right and left lower spar caps, approximately 1.25 inches inboard of the fracture. Up to a depth of approximately 0.045 inch the hardness ranged from 133 to 144 HK (138 Avg) for the left spar and 136 to 154 HK (146 HK Avg) for the right spar. Deeper than 0.045 inches below the spar surface the hardness ranged from 154 to 186 HK (168 HK Avg) for the left spar and 149 to 184 HK (168 HK Avg) for the right spar. Although these hardness values, are not directly convertible to HRB values for comparison to the above readings, they do indicate that the large grained surface was slightly softer, as indicated by ASTM E-384, than the finer grained interior zone.

Conductivity

Electrical conductivity was measured on the left and right lower spar caps. The measurements were made using a calibrated "Magnatest FM-120" eddy current conductivity test instrument. The conductivity measured on the lower surface of the left wing lower spar cap near the fracture ranged from 30.5 to 31.5% IACS. A similar location on the right wing lower spar cap measured 31.5% IACS.

Other Separations Left Wing

During the examinations of the other fractures associated with the left wing main spar separation, a small (0.07 x 0.03 inch) region of fatigue cracking was detected in the forward gusset web. The fatigue region was located in the horizontal web section just forward of the outboard forward spar attach bolt. This area is denoted by arrow "W" in figure 4. The remaining fracture area of the forward web and all the fracture of the aft web were typical of an overstress separation.

The upper horizontal flange of the forward gusset web was also fractured. The gusset flange was bent upward and overstress fractured in the areas around the upper attachment bolt holes.

Left Wing Upper Skin Cracks

Two portions of the left wing upper skin were received separate from the spar assembly section. Figure 10 shows the location of the two skin pieces in relation to the spar. The skin piece forward of the spar at the wing root area contained a 5.6 inch long crack (see bracket "A", figure 10) between 6 rivets attaching the upper skin to the most inboard wing rib. The outboard aft wing skin section was cracked at three locations adjacent to three skin to second inboard wing rib rivets. These cracks are identified in figure 10 by brackets "B".

At both cracking locations, there were non-original manufacture holes drilled through the skins at the locations of the cracks, as if the cracks had been "stop drilled" (see arrows "D" in figure 10).

Both sets of skin cracks were opened by making appropriate saw cuts through the skins to the crack ends and removing one face from each crack. Optical examination of the crack faces, after cleaning, revealed heavy rubbing damage to large areas of the forward inboard crack faces (bracket "A"). However, sufficient crack face details remained to identify fatigue progression features in the undamaged areas. The directions of the fatigue progression and the presence of slight offsets along the crack plane indicate the overall crack was formed by the intersections of six independent fatigue cracks. The independent cracks appeared to have initiated on the upper surface of the skin under the edges of the rivet heads.

Examinations of the crack faces from the outboard aft skin cracks (brackets "B") also identified fatigue progressions features. As with the inboard cracks, the fatigue cracks were determined to have initiated on the upper surface of the skin under the manufactured heads of the rivets.

Joe Epperson

Joe Epperson
Metallurgist

Attachments

TABLE A

BOLT LOOSENING TORQUES

BOLTS NUMBERS OUTBOARD FORWARD TO INBOARD AFT

| No. | Torque (ft.-lbs) |
| --- | --- |
| 1 | <15* |
| 2 | <15* |
| 3 | 25 |
| 4 | 30 |
| 5 | 30 |
| 6 | 35 |
| 7 | 30 |
| 8 | 35 |
| 9 | <30 |
| 10 | <20 |

*at fracture

Installation Torque 360-390 in lbs.

30-325 ft.-lbs.

TABLE B

Striation Measurements

| Location (see figure 7) | Avg. Striation Spacing (S/I) | Distance from Origin (in) | Cycles Spacing X distance |
|---|---|---|---|
| 1 | 87,500 | 0.19 | 16,625 |
| 2* | 66,982 | 0.27 | 5,359 |
| 3# | 37,644 | 0.49 | 8,282 |
| | Approximate Total (Conservative) | | 30,265 |

*Average of 2 measurements 72,631(S/I) and 61,333(S/I)

#Average of 3 measurements 36,571(S/I), 40,000(S/I) and 36,363(S/I)

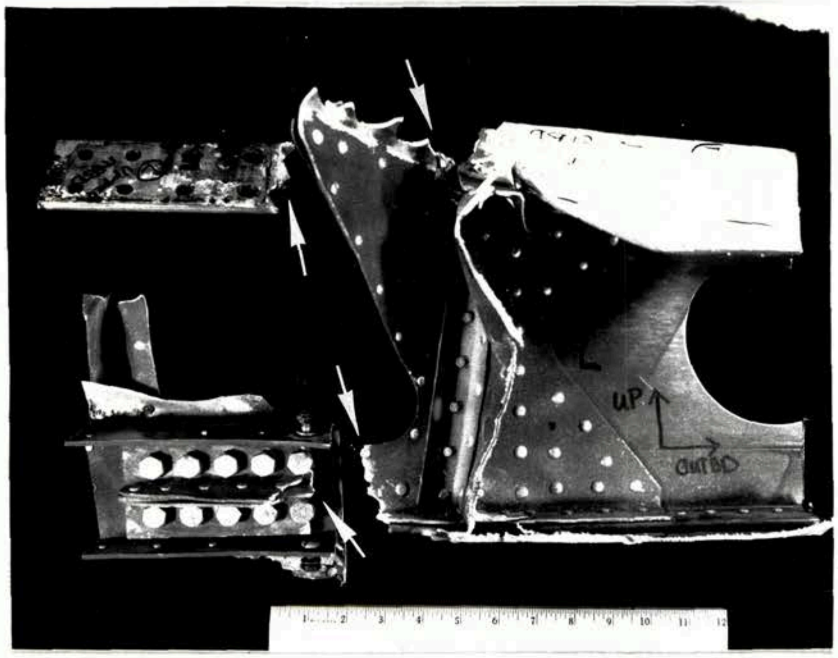


Figure 1. An overall view of the as-received left wing spar pieces with the fracture locations denoted by arrows.

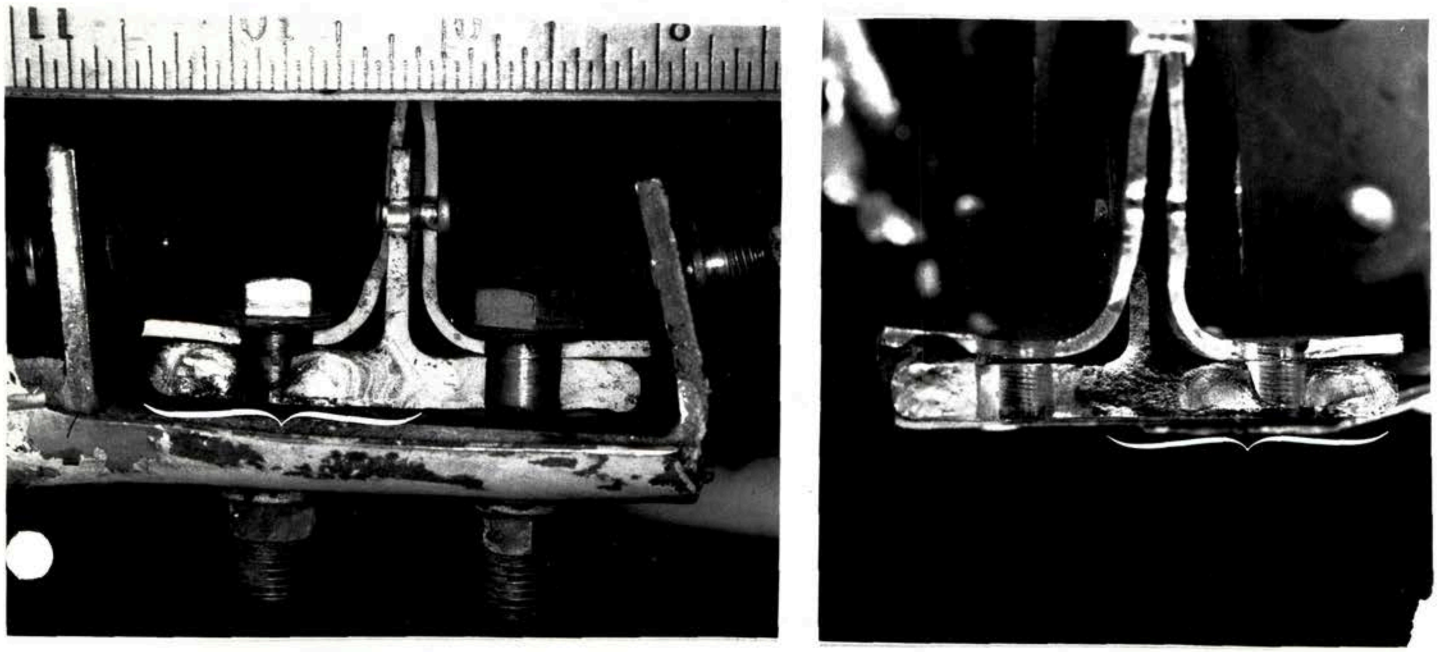

Figure 2. Inboard (left) and outboard (right) views of the lower spar cap fracture with the fatigue zones denoted by white brackets. Left view also shows fuselage carry through and attachment fasteners.


Figure 3. A view looking at the upper surface of the carry through at the forward outboard bolt hole (forward at right, outboard at top) showing the fretting demarkation lines which correspond to the spar fatigue planes.

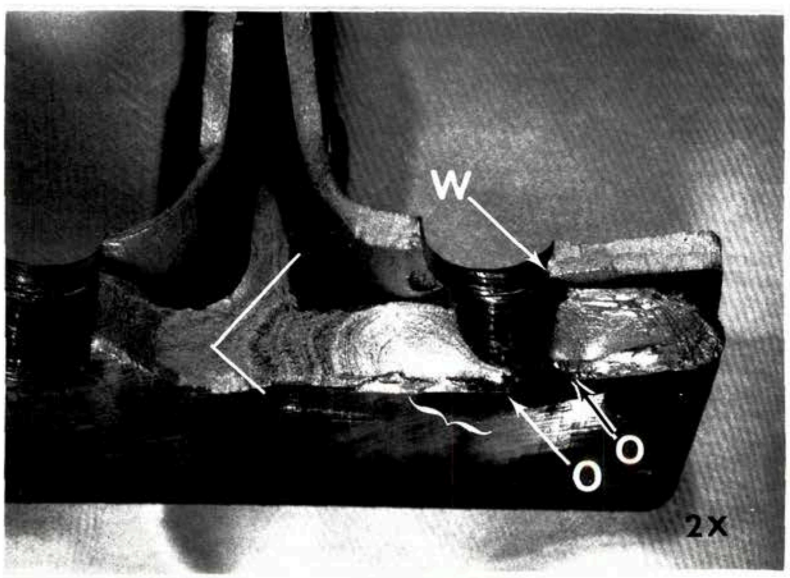


Figure 4. View looking outboard at the outboard spar fracture face with forward at right. The fatigue origins, arrows "O", and terminus white line, are denoted along with the lower surface fretting, white bracket, and location of web fatigue crack arrow "W".

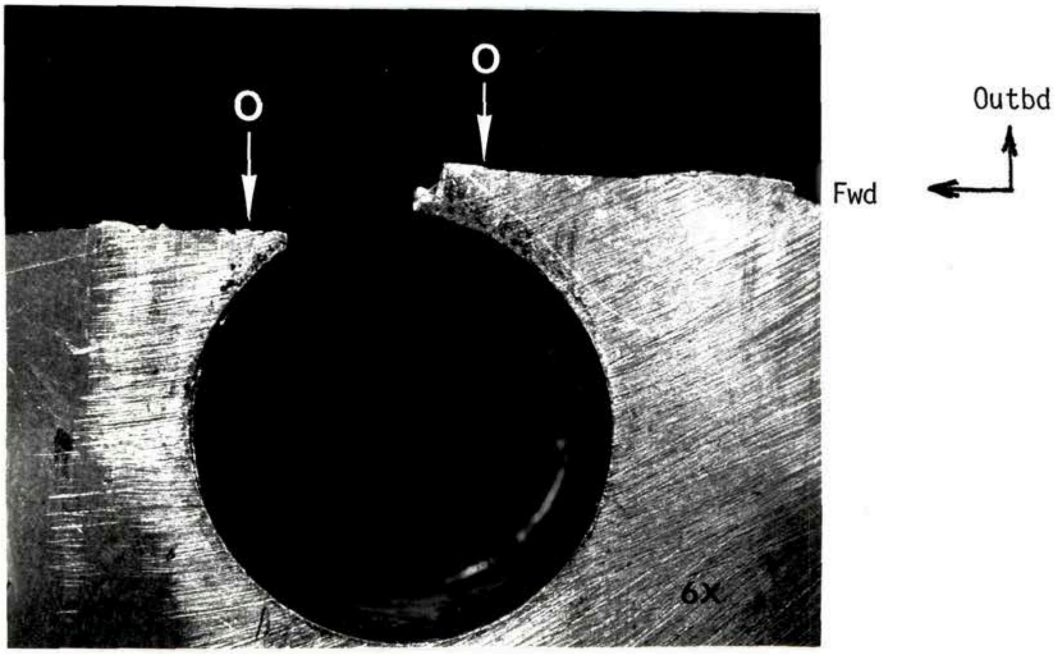


Figure 5. Photograph displaying the lower spar surface adjacent to the fatigue zones showing the relative positions of fatigue origins, planes and bolt holes. Forward at left, outboard at top.

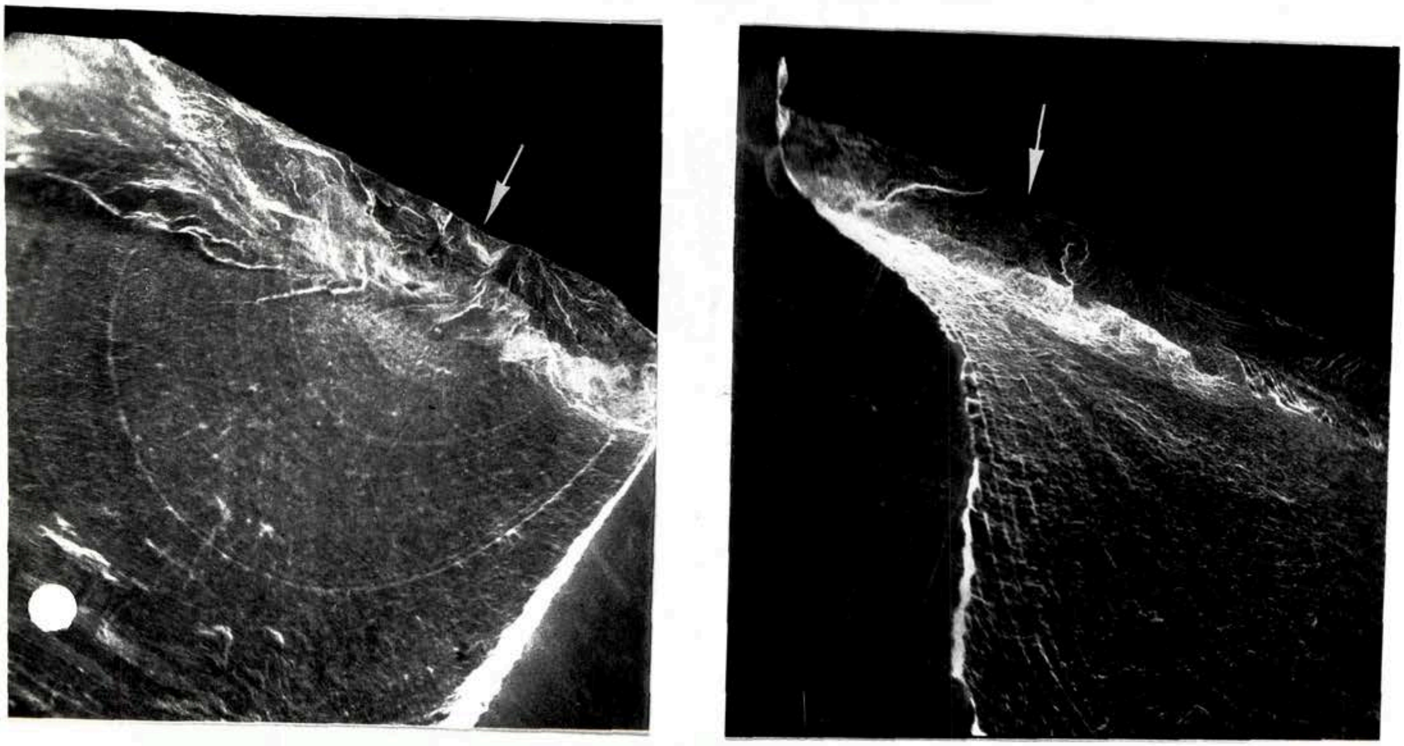

Figure 6. SEM macrographs (10X) of the two fatigue origins, forward fatigue plane at left, aft fatigue plane at right.


Figure 7. SEM fractograph montage of the aft fatigue plane showing the origin (Arrow "O") and centroid of progression (black/white lines). Circled number indicates approximate locations of striation spacing measurements.

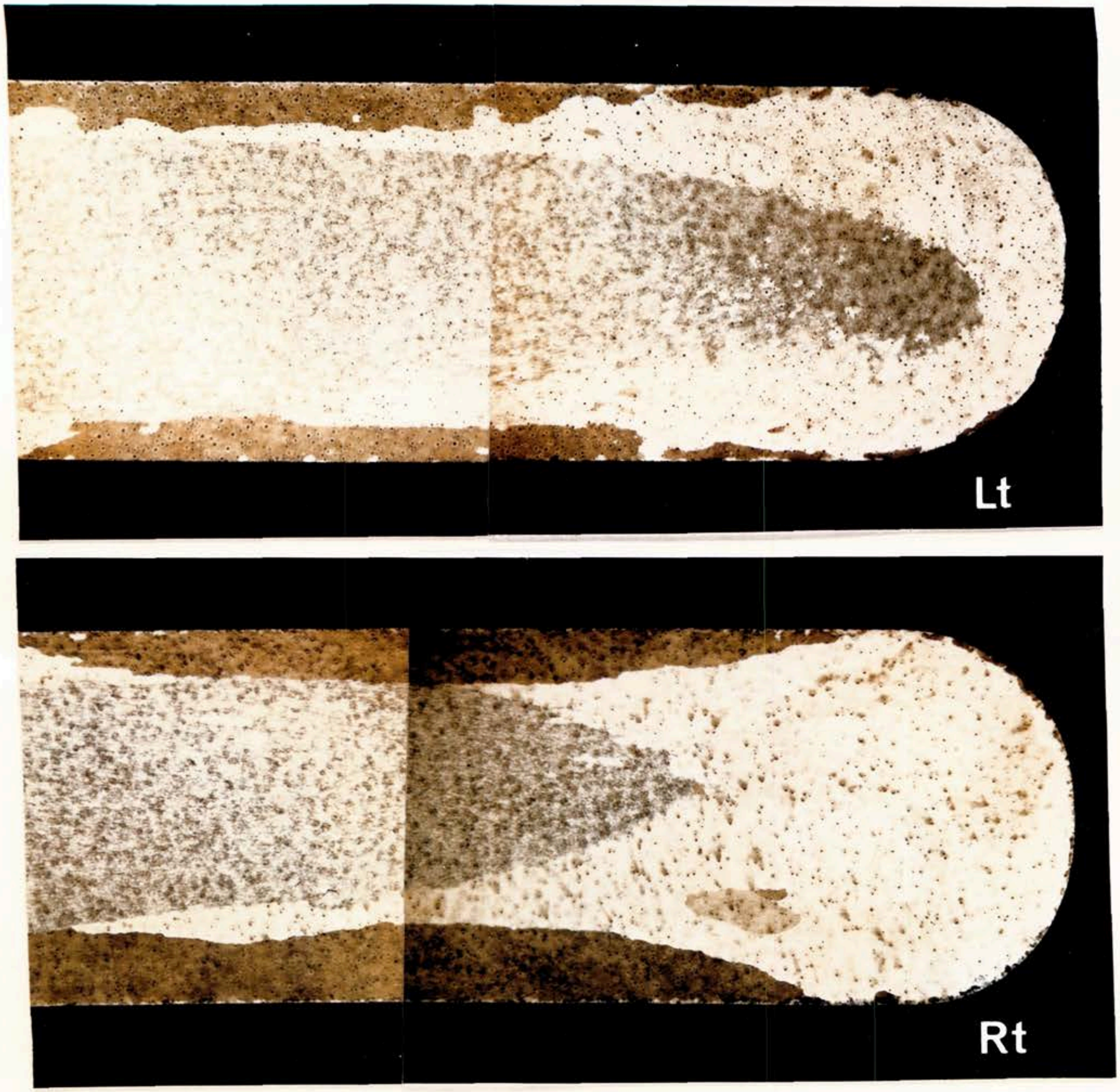


Figure 8. Micrographs of the left and right lower spar caps showing the typical microstructure. Keller's Reagent etch. (6.4X mag.)


Figure 9. Micrograph showing the metal flow layer, bracket "P" adjacent the left wing spar outboard aft attachment bolt hole.

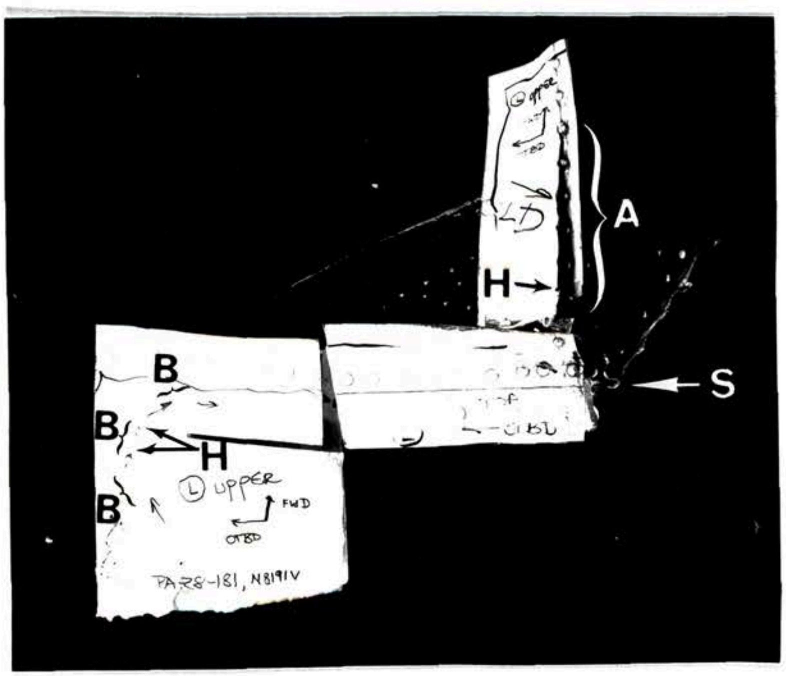


Figure 10. View of the additional upper skin pieces with the cracks at brackets "A" and "B". Stop drill holes at arrows "H" and spar at arrow "S".