X-735-66-406

NASA TM X-55607

SOME FAILURE PROBLEMS IN SPACECRAFT AND SPACE BOOSTERS

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

JULY 1966

N67 13223 (ACCESSION NUMBER)	(THRU)
42 (PAGES)	1 (CODE)
TMX-55607 (NASA CR OR TMX OR AD NUMBER)	31 (CATEGORY)

FACILITY FORM 602

NASA

GODDARD SPACE FLIGHT CENTER
GREENBELT, MD.

SOME FAILURE PROBLEMS
IN
SPACECRAFT AND SPACEBOOSTERS

By
A. J. Babecki
J. D. Grimsley
H. E. Frankel

July 1966

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

SOME FAILURE PROBLEMS

IN

SPACECRAFT AND SPACEBOOSTERS [1]

by A. J. Babecki, J. D. Grimsley, & H. E. Frankel [2]

INTRODUCTION

It has been said that "one picture is worth a thousand words", and that "one test is worth a thousand expert opinions". With equal proverbial truth, it can be stated that "a service failure is the ultimate test". Laboratory tests which are conducted under simulated service conditions render only approximate performance characteristics of a device or structure. Accordingly, such tests do not usually give a true picture of how a part or assembly will perform in actual service.

Admittedly, a service failure is generally a destructive test, and as such, it is costly and rarely planned. However, when it occurs, the service failure has much information to offer to the trained investigator to enable him to ascertain where the weak points lie so that a definite improvement can be made, as opposed to a temporary "fix". Unfortunately, too many times such failures are not investigated and analyzed to the depth and with the degree of professionalism that they deserve, and consequently, much valuable information is lost not only to those directly affected by the failure, but to science and industry as well.

In most instances, a service failure is retrievable so that analysis can be performed. Occasionally, as in the case of an aircraft failure, the parts are so widely dispersed or so badly damaged, that failure analysis becomes difficult, if not impossible. In the area of unmanned satellites and space probes, actual service failures are, for the present, irretrievable. Accordingly, when a failure in one of them occurs on launch, or afterward, failure analysis must be made by conjecture after simulated laboratory or ground tests. Spaceboosters, or first-stage launch vehicles, are sometimes recoverable and permit analysis of failure which might occur in them during the initial launch phase.

---

[1] Paper presented at the William Hunt Eisenman Failure Analysis Conference of the American Society for Metals, Waldorf Astoria, New York City, July 12-14, 1966.

[2] Mr. Babecki and Mr. Grimsley are Metallurgists and Dr. Frankel is Head in the Materials R&D Branch of the Goddard Space Flight Center, Greenbelt, Md.

Failures in spacecraft and spaceboosters can take many forms. These may be failures in metallic components which occur by rupture, or excessive deformation, or by corrosion. Failure can also occur as a result of properties which are too good. For example, in the case of an explosively-operated bolt cutter which was part of a system to separate the spacecraft from the launch vehicle, failure occurred because the bolts were too tough to be severed by the cutter. Failures of metallic components may range from large-size structures, such as fuel tanks of launch vehicles, to microscopic elements, such as half-mil diameter lead wires in electronic devices.

Other failures in spacecraft do not involve metals at all. For example, the evaporation of lubricating oils and greases in vacuum which causes bearing and gear torques to increase prohibitively; or the discoloration of paints under ultraviolet radiation from the sun which changes the absorptivity/emissivity ratio and causes the spacecraft or experiment to reach disabling temperatures; or the outgassing of polymeric materials in the vacuum of space and the redeposition of these condensable molecules on cooler optical and mirror surfaces, with a resultant loss in transmission or reflection; or the development of corona discharge or high voltage arcing in electronic components which cause power failures.

Although the failures which occur on spacecraft involve a variety of materials, this paper will present several examples of common failures which are related only to metallic components. They are, in all cases, failures which occurred during simulated service testing, rather than in actual service.

CAUSES OF FAILURES

Because of the great expense involved in the total picture of a satellite launch, the NASA strives for the ultimate in a practically obtainable reliability. As a result, performance tests are conducted on all parts as individual components, subsystems, systems, and then as fully-integrated spacecraft. Those tests which induce mechanical stressing or affect the mechanical properties of metallic components include vibration, acceleration, decompression, vacuum, corrosion, and thermal exposures.

During such tests, failures of metallic components occur for several reasons. Some are attributable to excessive stressing which occurs as a result of unrealistically-high vibrational specification requirements.

Uncertainties in the vibrational spectrum and intensities to be experienced during launch are generally the reasons for high specification requirements. Although previous tests and launches with the vehicle to be used had given usable and reliable vibration data, unknown multiplication factors and damping characteristics of the various component designs and materials account for the uncertainties.

Other failures are attributed to exhaustion of the fatigue design life of the part simply because it was subjected to an excessive number of repeated mechanical tests as various components and systems were added, or as design changes were made which required retesting for requalification. One must remember that in space applications, weight is a serious consideration because of launch vehicle thrust limitations. Accordingly, spacecraft structural components are designed with very small safety factors and with relatively short fatigue lives, inasmuch as they are subjected to service vibrational stresses only during the short period of the launch phase. Then, too, the design life is usually based on data developed on smooth, perfectly-machined test specimens tested under uniform and exactly-known stresses. These conditions are never achieved in service. Besides, most spacecraft hardware are coated with platings, oxide or chromate or other conversion coats, or have surfaces which have been altered by diffusion processes, such as carburizing or nitriding. All of these conditions may alter the fatigue characteristics.

Unfortunately, many failures are the result of improper processing and inspection during fabrication. Poor machining practice produced parts which did not conform to the drawing and which were not rejected, resulting in sharp stress concentrations on cyclically-stressed parts that caused fatigue failures during vibration tests. Improper heat treatments also were responsible for early failures during testing. Welding performed on heat treated aluminum to add reinforcing brackets actually did more damage than good, as the welding heat reduced the strength in the heat-affected-zone and resulted in cracking during vibration testing.

The selection of improper materials also is responsible for a percentage of the failures. For instance, a high-silver brazing alloy was used to make brazed joints in a stainless steel assembly on a spacecraft damping system which employed liquid mercury as the damping medium. Leakage developed in a matter of days as the mercury alloyed, or amalgamated, with the brazing alloy and caused liquid metal corrosion. Other failures occurred when leaded phosphor bronze was used as a material for fine-toothed gears. In this application, the gears were machined from bar stock in which the gear tooth axis was parallel to the working direction of the bar. This resulted in large inclusions being oriented normal to the stress direction, as shown in Figure 1, such that they served as minute stress concentrators which precipitated failure at the root of the teeth during vibration testing. The lead inclusions also significantly reduced the effective cross section of the phosphor bronze.

Additionally, failures occur because of improper design. This has been true especially in regard to the use of brittle alloys in thin sections, such as the aluminum casting alloy 356 and a very high silicon (20%) aluminum alloy. Mechanical properties for these and other materials, which are quoted in handbooks or data sheets, invariably are based on specimens which are not at all similar to the actual part being designed. Accordingly, microporosity, surface condition, and microstructural differences in the part as a result of the casting size and shape, founding process, and other factors, may greatly reduce the mechanical properties below the calculated design level. On spacecraft, complex-shaped, thin-walled aluminum and magnesium castings are often used, but too often with fillets and radii that are too small.

EXAMPLES OF SPACECRAFT FAILURES

The failures to be discussed in the following paragraphs are examples of but a few of the many which occurred in unmanned scientific satellites during the course of testing of prototype, or engineering, models. This is not to say, however, that the actual flight hardware does not ever fail. Hopefully, the prototype failures effect changes, if necessary, in design, materials, workmanship, or testing requirements so that failures in flight hardware are at an absolute minimum.

Corrosion

Concentrated hydrogen peroxide is used on such satellites as Syncom, and Early Bird, and the Applications Technology Satellites for attitude control. Because these are relatively long-life spacecraft (1 - 5 years), it is imperative that the peroxide be kept in as stable a condition as possible. For this reason, the storage tanks, lines, fittings, and valves are made from pure aluminum (alloy 1060 with 99.6% min. purity) which is reported to be the metal least catalytic to the decomposition of the peroxide. In the conditioning of the aluminum to render it passive to the peroxide, it is subjected to 70% and 35% nitric acid for 11 or more hours. The system is then charged with 90% concentration hydrogen peroxide and monitored for passivity. At this time, some fittings were found to develop leaks.

A typical fitting is shown in Figure 2 against the cross section of the extruded 1-1/2" diameter bar from which it was machined. One of the fitting legs is also pictured at higher magnification to reveal the appearance of a leak (encircled) that was approximately two mils in diameter. In all cases, the holes developed in a direction parallel to the longitudinal direction of the extruded bar.

Figure 3 pictures a radius cross section of the bar after polishing and chemical etching. The elongated flow pattern of the structure is evident as well as the refined grain size at the outer surface caused by some subsequent cold working. As the alloy is quite pure, the inclusion rate was quite low, and no stringer formation could be noted. Accordingly, the etching out of inclusions could not be the reason for the hole development.

Electron microprobe scans were made on the longitudinal and transverse cross sections for the more common trace elements, iron, copper, silicon, and manganese. Only iron was detected as being concentrated at spots that measured 0.2 - 0.3 mil in diameter, and the iron concentrations at these spots were as high as 35%. Some of these high-iron spots occurred in clusters, as seen in the transverse section of Figure 3. In the longitudinal section, these spots are greatly elongated and could serve as paths of leaching by the acid and peroxide.

This possibility seemed to be confirmed by subsequent tests in which thin transverse slices of the bar were subjected to annealing treatments at 1100°F for 1 and 16 hours. Following each of these treatments, which permitted diffusion to minimize the iron concentrations, the populations of the corrosion pits that developed were successively and significantly less. The 1 hour exposure about halved the population and the 16 hour exposure reduced it by about an order of magnitude.

Fatigue

Probably the most common failure mechanism for spacecraft hardware is that of fatigue. It has been experienced in fixed components, such as equipment brackets and deck panels; in rotating hardware, such as shafts and ball bearing separators; and in near-microscopic electronic applications, such as half-mil diameter gold lead wires in transistors. Other so-called static fatigue failures also have occurred in high-strength steels that had been electroplated. In one case, the separation band, which holds the spacecraft onto the vehicle, fell off just prior to launch. A 4340 clamp on the band, which was heat treated to high hardness and then cadmium plated, fractured in a brittle fashion through a hardness indentation. Investigation later disclosed that it was embrittled by hydrogen evolved during plating.

A rotating fatigue-type failure occurred in a hermetically-sealed tape recorder wherein the reel shaft failed after several hundred hours of operation and after vibration testing. Other than the vibrational stresses periodically imposed, the only other stresses experienced by the shaft were the alternating tensile and compressive stresses imposed on the rotating shaft by the fractional-pound eccentric pull of the tape. The shaft was type 416 stainless steel.

A typical shaft is shown in Figure 4. The failure occurred at the 0.270" diameter relief undercut adjacent to the upper shoulder. Although the drawing for this shaft called for a 20-mil radius to the undercut, many were found with radii of less than 10 mils. A sample of such an undercut is also pictured in Figure 4. The width of the undercut is 40 mils; therefore, it should exhibit a smooth, fully-concave surface.

Initial failure analysis by the contractor termed it a brittle failure caused by impact during vibration. Subsequent analysis by the authors termed it a fatigue failure due mainly to the stress concentrating effect of the 6 mil radius measured in the undercut notch. A macroscopic view of the fracture surface shown in Figure 5, gives faint hints of concentric rings to indicate fatigue crack propagation. However, fractographs made by the electron microscope at 16,000X, also shown, definitely revealed the parallel striations typical of fatigue failures.

Although the 416 stainless steel exhibited a large amount of free ferrite in its microstructure and large sulfide inclusions, which improve machinability, these factors were not as contributory to the failure as the poor machining practiced.

Extreme Brittleness

One of the fears that spacecraft experimenters have is that of cold welding between metal surfaces in contact in the ultra-high vacuum of space. To prevent this from happening, various schemes are employed. These include hermetic sealing of the moving parts in an atmosphere of nitrogen or air or other gases, the use of oils and greases and solid-film lubricants, the formation of non-metallic films or coatings on the metal surfaces such as anodized oxide films on aluminum. Another technique employs materials of high surface hardness in contact.

This last technique has been used quite frequently on gears and rachets, and with considerable trouble. Such alloys as Nitralloy 135 or type 416 stainless steel have been used for very small gears and given a high surface hardness by nitriding processes. Unfortunately, the small size of these parts requires extreme control over the nitriding process to prevent an excessive depth of the hardened case. Apparently in many such applications such fine control was not practiced and, consequently, extremely brittle gears were produced which failed in normal operation or during vibration testing of the system.

Figure 6 illustrates one such application. This is a rachet wheel which was part of a driving mechanism for a spectrometer grating. It measured only 1/4" in diameter and had teeth that were only 11 mils in slant height. It was made of Nitralloy 135M. and had a mating pawl of C 1095 steel hardened to 50 Rc. Although the contractor was to use gold plating and molybdenum disulphide as solid lubricants on the rachet wheel, nitriding of the wheel to minimize cold welding was also practiced.

As shown in the photograph, this procedure produced extremely brittle teeth which were subject to early failure in operation, and even during handling in assembly. Figure 7 presents etched transverse cross sections of broken and nonbroken teeth at 200X and 375X respectively, which indicate that instead of a thin nitrided surface, the process produced complete hardening of the tooth volume. Micro-hardness measurements disclosed that a hardness of 65 Rc was obtained to a depth of 7 mils, which was more than half the slant height of the rachet tooth.

In addition to the highly embrittling effect, the nitriding process also placed the surface material in compression, which normally is a desirable condition. But on external angles, such as the rachet or gear teeth, this high compressive stress places the subsurface volume in tension and produces the tendency for spalling or cracking. This residual stress, coupled with the service stresses, was sufficient to cause the breakage noted.

A change of material for the rachet wheel to an air or oil hardening steel, such as 4340, eliminated the problem, and although the surface hardness was reduced from 70 Rc to 55 Rc, it was found to be adequate to prevent galling or cold welding.

Anisotropy

Many failures occur because the design stress is actually higher than the tensile strength of the finished part. This may be due to the fact that design stresses are based on handbook values of properties which may differ radically from the material in question. Book values are generally based on tests conducted with optimum specimens under optimum test conditions. Failures of finished parts occur under non-optimum conditions. In other cases, a material may be so worked during processing that it exhibits strong anisotropy, especially in such properties as ductility. This has been a problem on aluminum clamps which are used to hold the spacecraft onto the spacebooster or onto an adapter section between them.

The aluminum clamps are arc sections from a roll-forged ring of 2014 alloy heat treated and strained to the T652 condition. These 18" X 1/2" X 1/2" sections are machined into a U cross section to clamp together the flanges of the spacecraft and adapter. The sections are riveted as shoes to two stainless steel bands which are joined together by explosive bolts. Tightening of the bolts during assembly strains the bands and compresses the shoes against the flanges. This action, of course, tends to open the U cross section of the aluminum shoes, and a number of them have cracked as a result.

Figure 8 shows three views of one such cracked shoe. In all failures of these shoes, the crack originated at an end. An important element in these failures is the fact that the ring forging from which the shoes were cut had a smaller radius than that of the flanges which they held together. Accordingly, in this Marman-type band, the shoes were stressed mainly at their ends where existing corners and machining marks aggravated the stress situation. The thickness of the web at the base of the U was 0.20" and the radius of the U corners was 0.080". In other words, the alloy was being stressed in its short transverse direction by a wedge action which concentrated the stresses at the 80 mil corners.

Figure 9 presents photomicrographs of the longitudinal and transverse sections in direct light at 150X and 100X, respectively, and the transverse section adjacent to the crack under polarized light at 500X. The longitudinal section delineates the grain boundaries clearly; however, the transverse section reveals a cellular structure, especially under the polarized light. It is noted that the crack predominantly follows along the cellular paths. Figure 10 indicates that these cell boundaries, or bands, are more brittle than the material within them. This accounts for the difference in ductility exhibited by the alloy between the longitudinal and transverse directions, viz. 10% vs 2%. Electron microprobe examination did not disclose any compositional heterogeneity which could account for the bands. It is assumed that they represent varying dislocation densities, such as the flow lines in forged steel. Proposed solutions to the problem included a change in radius of the forged ring to one slightly larger than the flanges so as to load the center of the shoes rather than the edges, and a change in forging practice so as to forge the ring into a rough U cross section.

SOME SPACEBOOSTER FAILURES

Sounding rockets, such as the Aerobees and Nike-Cajun, and larger vehicles, such as the Thor-Delta, are the primary spaceboosters used for scientific satellite and space experiment launchings by the Goddard Space Flight Center. These vehicles have been highly successful over the past five years.

Despite the good record of successful launches, these boosters have not been without problems. When one considers the thousands of individual parts which go into a rocket assembly, each of which must have optimum reliability in operation, it is not surprising that a good bit of testing must be conducted and that some failures occur.

One of the reasons for these failures is the long chain of procurement that often exists. It may extend from the prime contractor through two or more successive subcontractors and through several successive processors and vendors. Such a long chain of responsibility for high-reliability hardware is difficult to police, and too frequently, shoddy workmanship or the use of defective material at the vendor or processor level is not detected until final assembly, or until a failure occurs.

Defective Steel

Thrust chambers for the Aerobee rocket sustainer stage are of double-wall construction which are cooled during firing by the flow of fuel between the walls. Figure 11 shows such a thrust chamber with the outer wall of 410 stainless steel removed. The inner wall is machined from a forging of 347 stainless steel to give the proper nozzle contour.

Inasmuch as the liquid fuel coolant circulates between the walls under a positive pressure before being injected into the combustion chamber, the construction must be leak-tight. A problem arose when a number of completed thrust chambers failed a leak test. Metallographic investigation of the failures disclosed that the 347 stainless steel chambers were machined from an exceptionally dirty heat of steel which actually should have been rejected at the forging stage. Associated with the non-metallic stringer inclusions were voids which caused the leakage. An example of the stringer inclusions is shown in Figure 11.

It was learned that the forgings received only a 25% inspection rather than the 100% called for. To correct this problem, the vendor was required to conduct 100% ultrasonic and dye-penetrant inspection on all forgings as well as macrographic examination of both ends of each forging billet.

Defective Processing

During leak testing of some Aerobee type 410 combination fuel-oxidizer tanks, leakage was noted in the region of the hemispherical head-to-shell weld, shown in cross section in Figure 12. This was found to be the result of stress corrosion as a result of faulty processing.

During fabrication, the head was fillet welded to the inside of the cylindrical shell about 1/8" from the shell end, which had a series of small diameter holes to serve as weep holes during final welding. In the final welding step, the remaining cylindrical shell was welded to the head and shell assembly, as indicated in the sketch. Heat treatment followed welding, and an acid pickling and descaling treatment was used to remove heat treatment scale.

Metallographic examination of trepanned samples from the suspect area revealed the stress corrosion cracking seen in Figure 12. Cause of the cracking was attributed to the entrance of acid into the faying surface cavity through the weep holes during the pickling operation and the failure to remove all of the acid during subsequent washings. The corrective action here consisted of sealing the weep holes prior to the acid exposure.

Defective Fabrication

Thin burst diaphragms are employed in the Aerobee sustainer fuel and oxidizer valves to permit flow of these liquids when proper pressure is developed. The oxidizer diaphragms are designed to rupture at a pressure of 190 to 210 psig, while the fuel diaphragms are to rupture at a pressure of 325 to 350 psig. Difficulty has been experienced in providing diaphragms with predictable burst strengths.

As designed, the diaphragms are to permit the oxidizer to begin flowing before the fuel. If they so operate that the fuel flows before the oxidizer, then a "hard" start can occur which may cause major structural damage to the combustion chamber, tubulation, or valves.

The diaphragms are made from 20 mil sheet of 3003 aluminum in the H14 temper. Bursting strength is controlled by the depth of a V-shaped circular groove which is coined into the aluminum sheets. The non-reproducible performance of the diaphragms was traced to variations in the depth and contour of the embossed V grooves. Figure 13 illustrates the kind of variations which were obtained.

The problem of this defective fabrication was further compounded by ineffective or lax inspection. Rectifying procedures called for closer control over the coining die contour and over the operation and better inspection immediately following the coining step.

CONCLUSION

It has been shown that failures can be the result of less than optimum conditions not only in materials and design, but also in fabrication, testing, and inspection. The production of high-quality high-reliability hardware is a team effort. Accordingly, all members of the team should be informed of the importance of their particular contribution.

Those companies which conduct educational or orientation sessions for their workmen to acquaint them with the part their work plays in the whole scheme of a structure, such as a spacecraft or a spacebooster, find that they have a very low rejection rate. Such an indoctrination program instills in the engineer, supervisor and workman a sense of pride in their work. Their suggestions or improvement should be solicited. It should be driven home that the money wasted by the Federal Government on defective hardware is actually their money, and they can and should help to eliminate this waste.

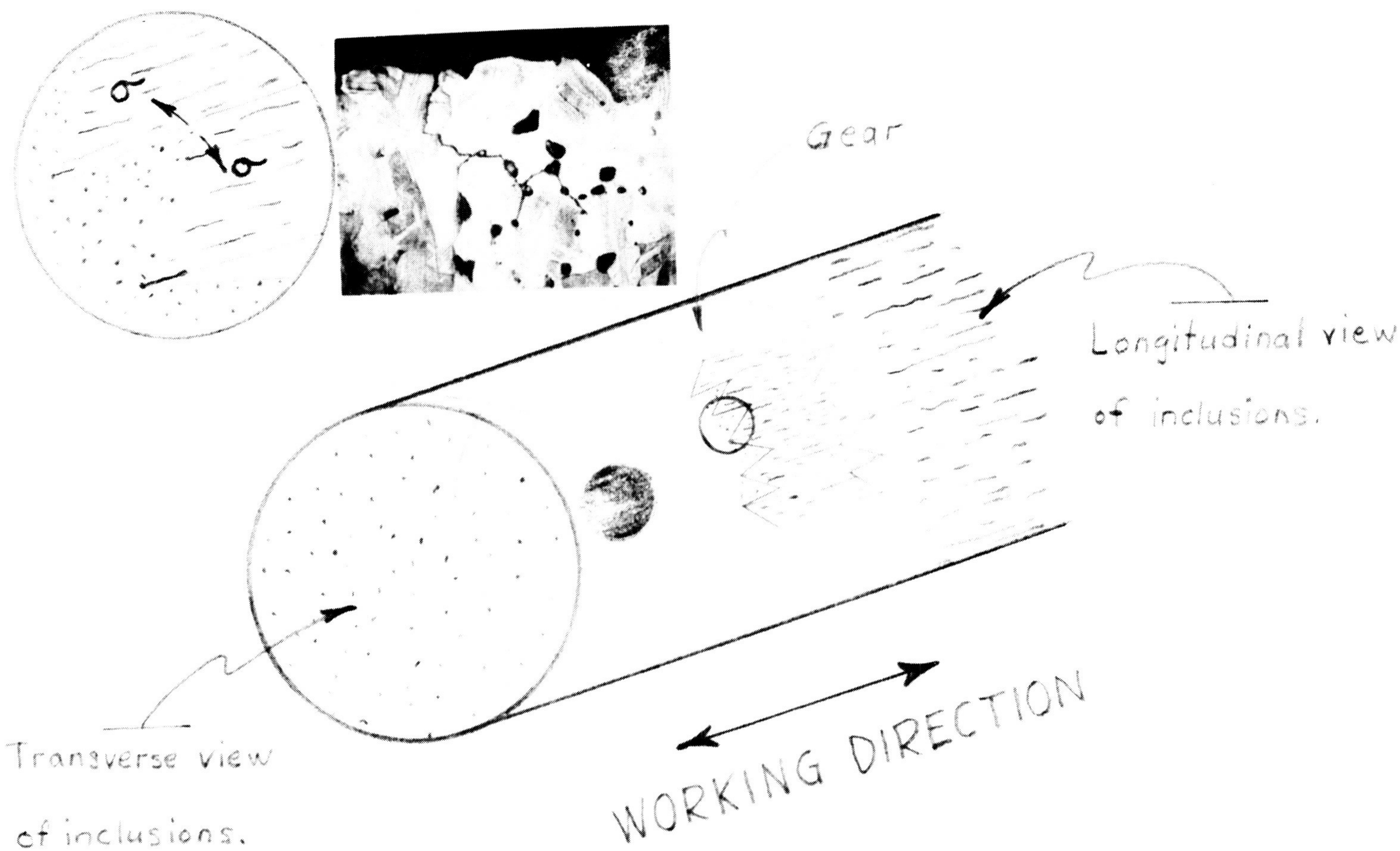


Figure 1. Schematic representation of inclusions in wrought bar stock and manner in which they may cause premature failure in gears. Photo insert shows cracking in the root of a gear tooth propagating between inclusions. Transverse section at 500X. Ferric chloride etch.

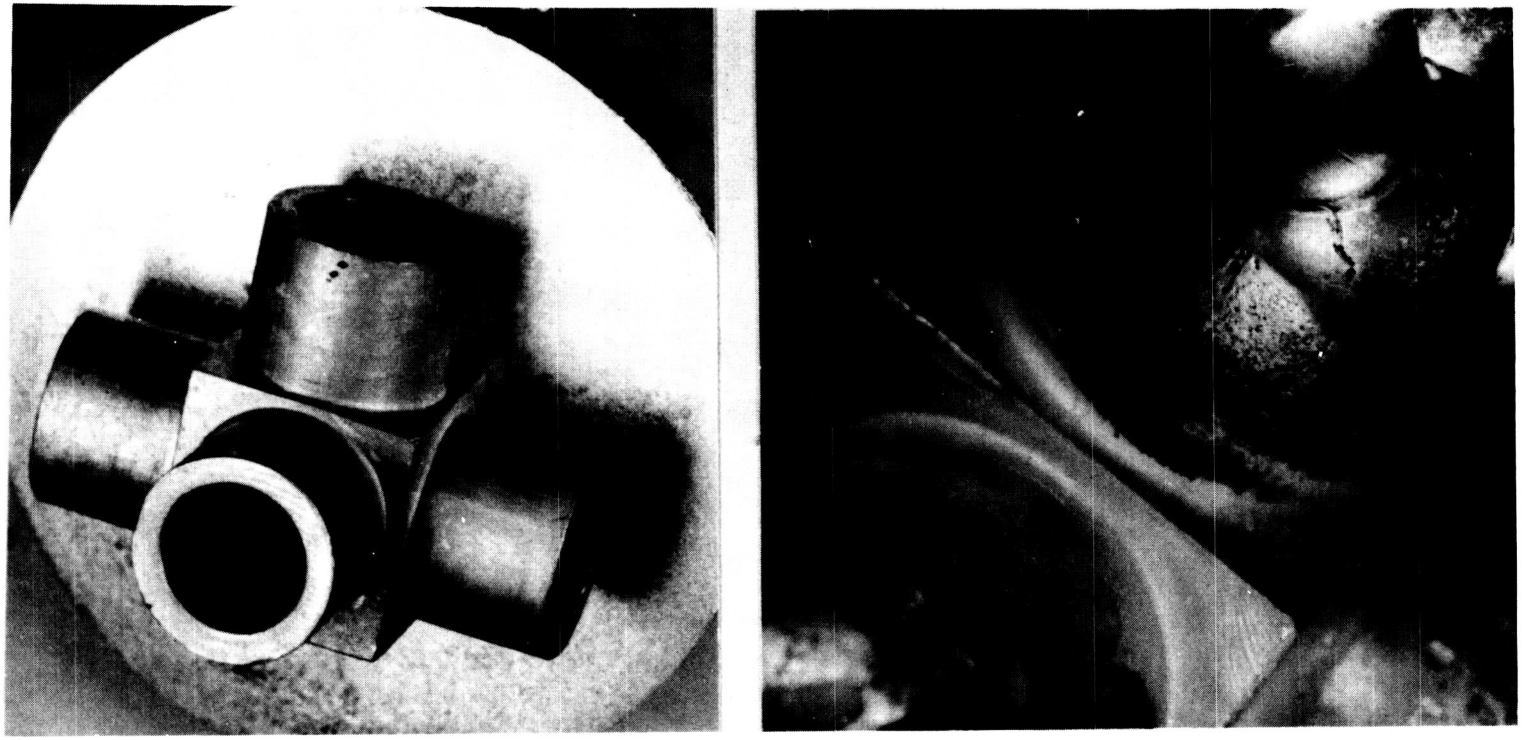


Figure 2. Fitting for concentrated H_2O_2 service machined from 1060 aluminum extruded bar stock. Orientation of fitting in bar cross section is shown at left; close-up view of leaking corrosion hole (encircled) is pictured at right.

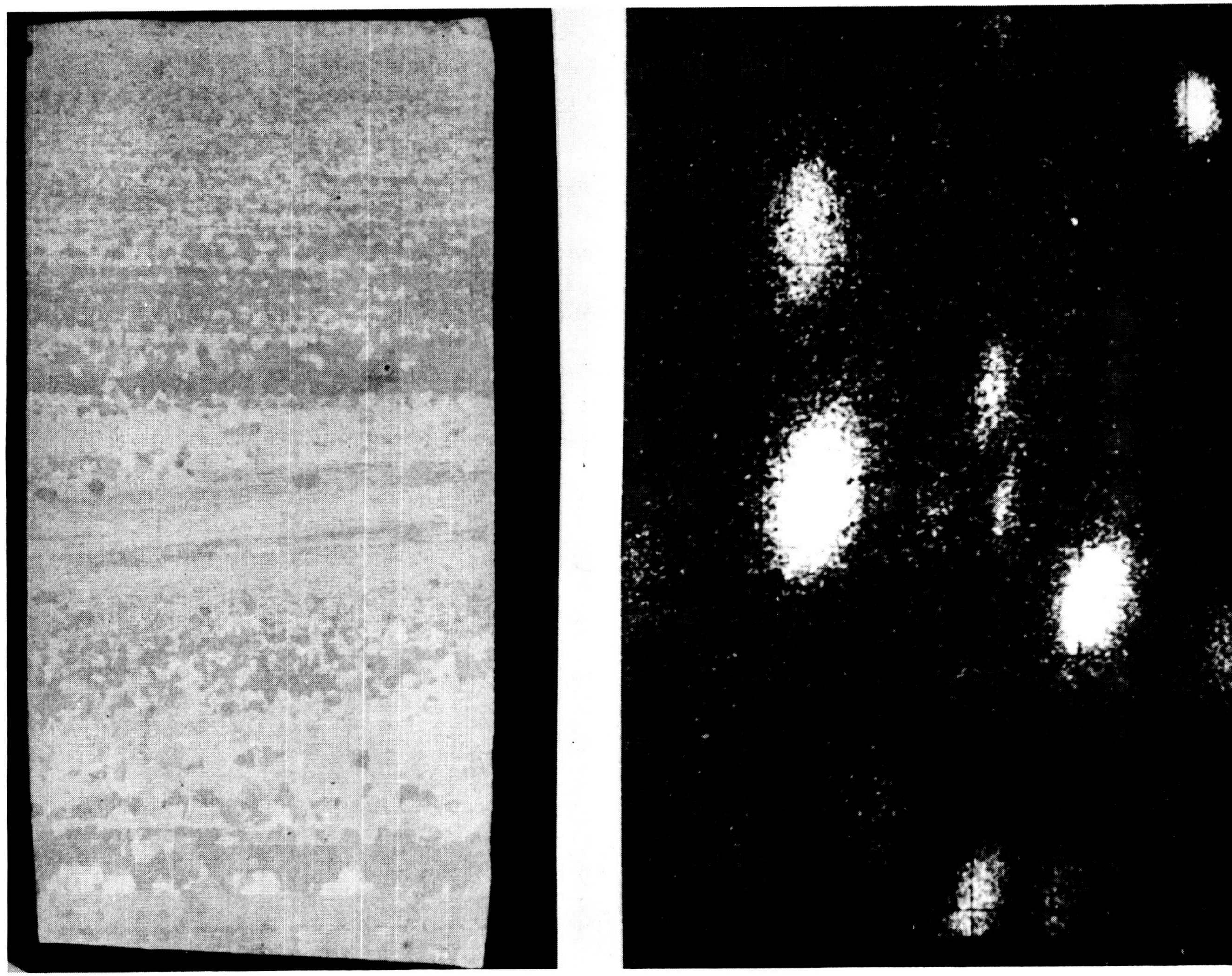


Figure 3. Longitudinal plane through a radius cross section of the 1060 aluminum bar after exposure to hot 70% HNO_3 (left). X-ray image at 1775X of iron concentrations (bright spots) in transverse cross section of bar, on right, made by electron probe microanalyzer.

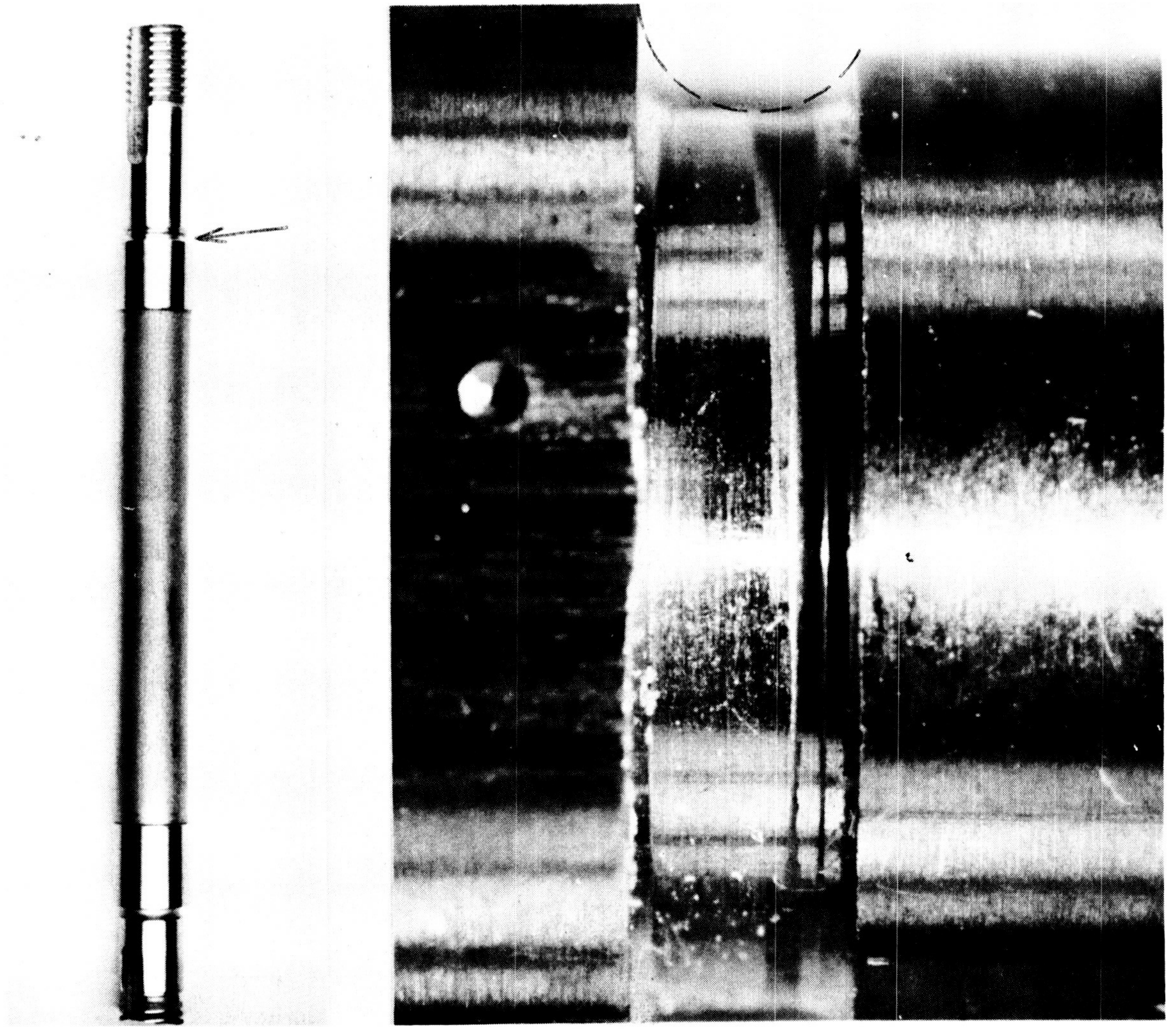


Figure 4. Tape recorder reel shaft (left) with failure location indicated by arrow. Enlarged view of undercut area (right) with specified radius shown by dashed line.

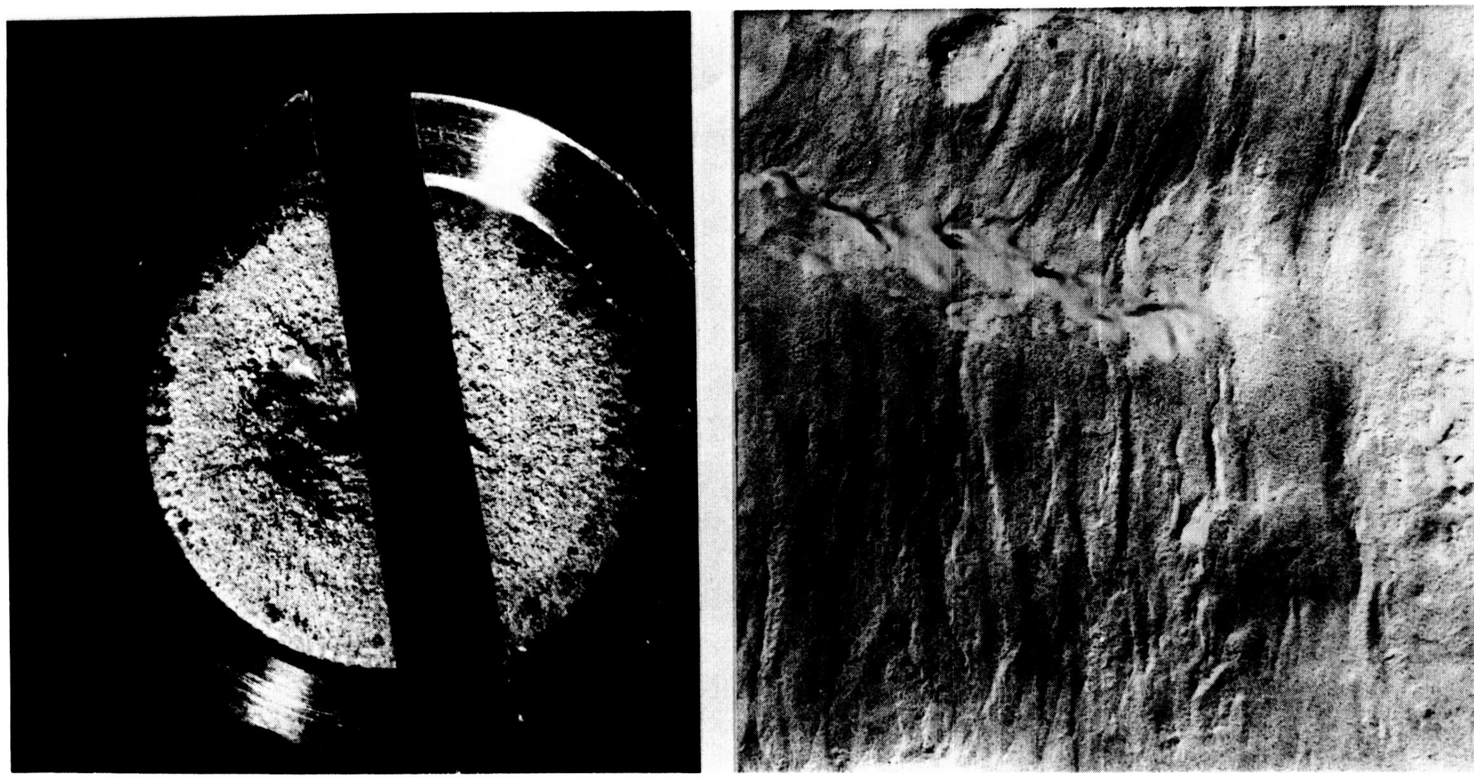


Figure 5. Macrograph of fracture face of tape recorder shaft at 12X (left) and electron fractograph of typical area on fracture face at 16,000X (right) both indicate fracture by fatigue crack propagation.

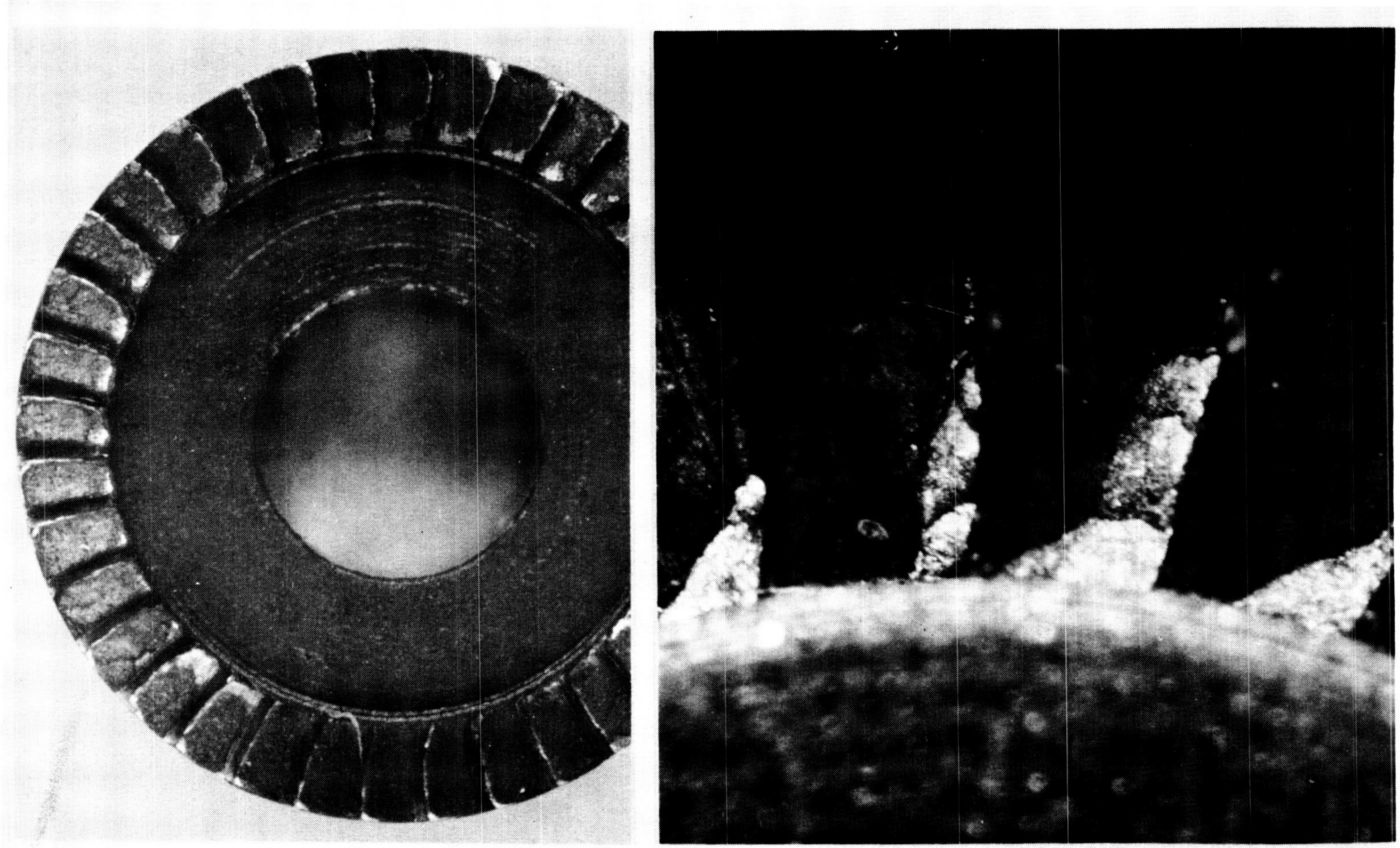


Figure 6. Rachet wheel (left) from spectrometer grating drive which suffered chipping of nitrided teeth, as shown at higher magnification (right).

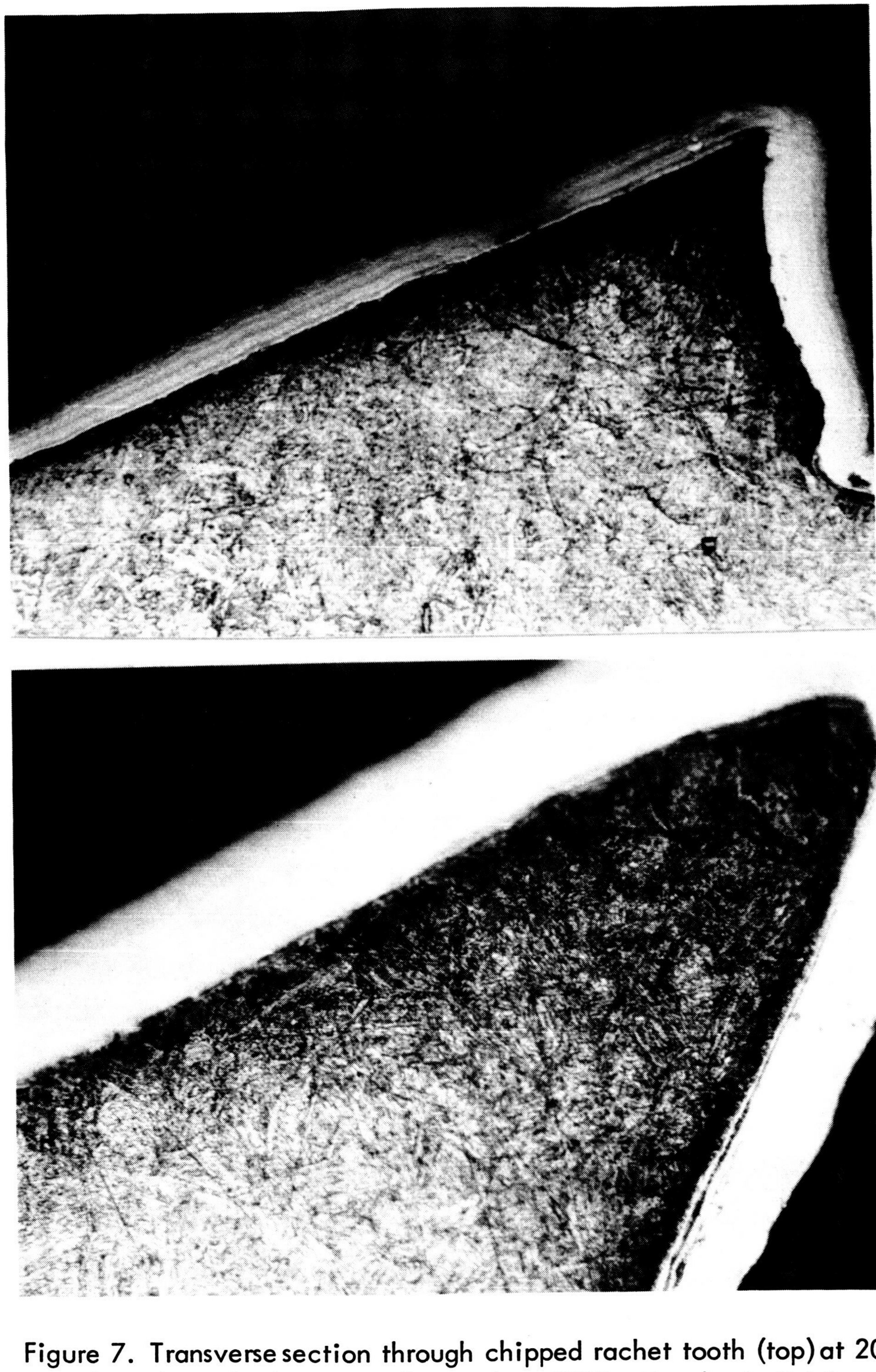


Figure 7. Transverse section through chipped rachet tooth (top) at 200X and through nonbroken area (bottom) at 375X. Depth of nitriding revealed by nital-etched dark area.

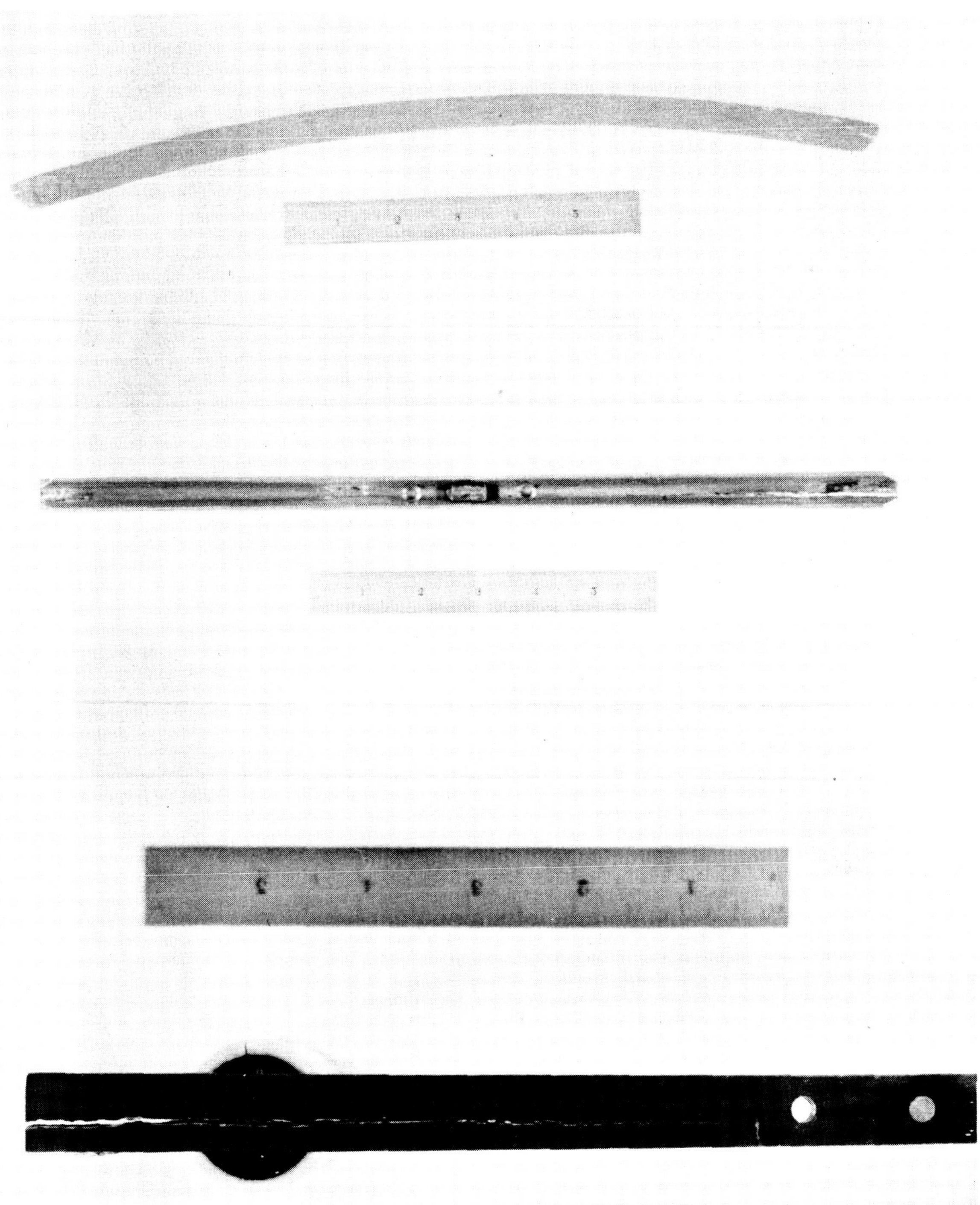


Figure 8. Three views of 2014-T652 aluminum shoe from spacecraft separation band with crack progressing from end.

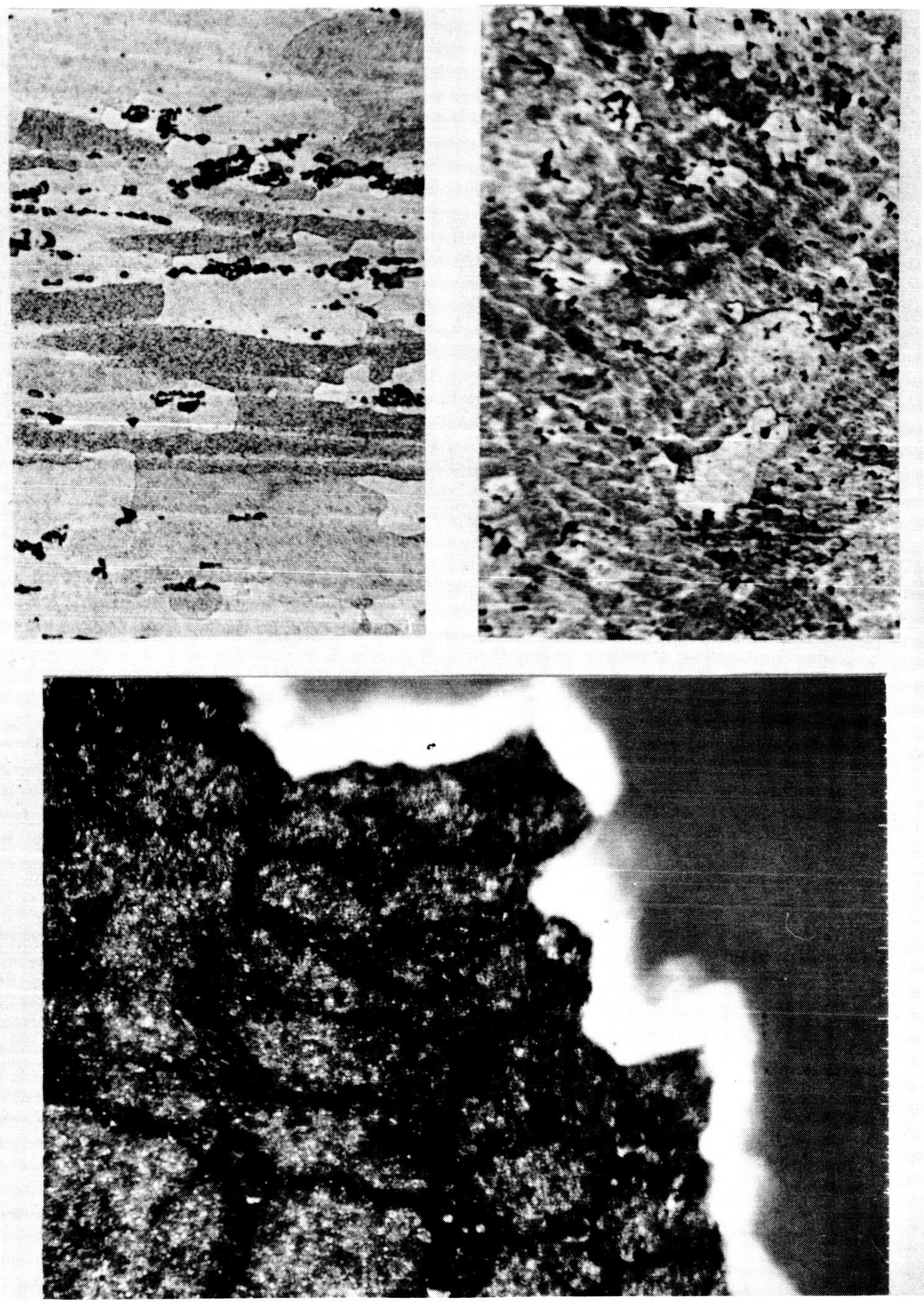
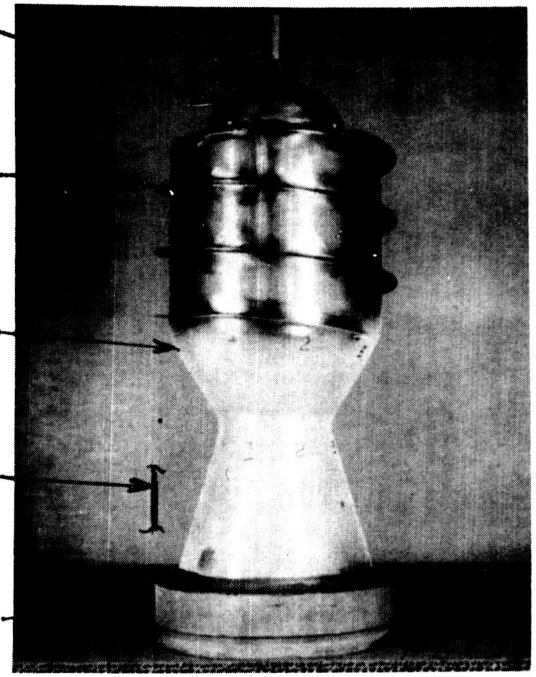
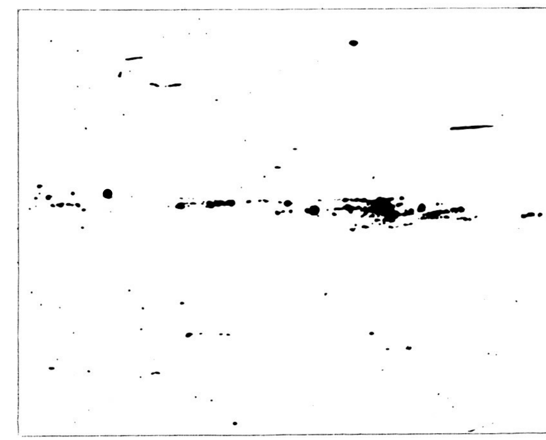


Figure 9. Longitudinal and transverse views of 2014-T652 aluminum shoe (top, left and right) at 150X and 100X, respectively. Light bands outline cellular structure which is elongated in longitudinal direction. Under polarized light at 500X, cellular structure in transverse plane (bottom) is outlined by dark bands.

Figure 10. Elongated cellular structure in longitudinal plane along fracture edge under polarized light showing evidence of ductility transverse to the cellular bands (top) and a lack of ductility parallel to the bands (bottom). Magnification 375X. HF-H_2O etch.



THRUST CHAMBER



X 100

INCLUSIONS PRESENT IN LEAK AREA OF DEFECTIVE CHAMBER LINER.

Figure 11. Aerobee rocket thruster with outer shell removed. Leakage through inner shell wall was caused by inclusion stringers such as that shown.

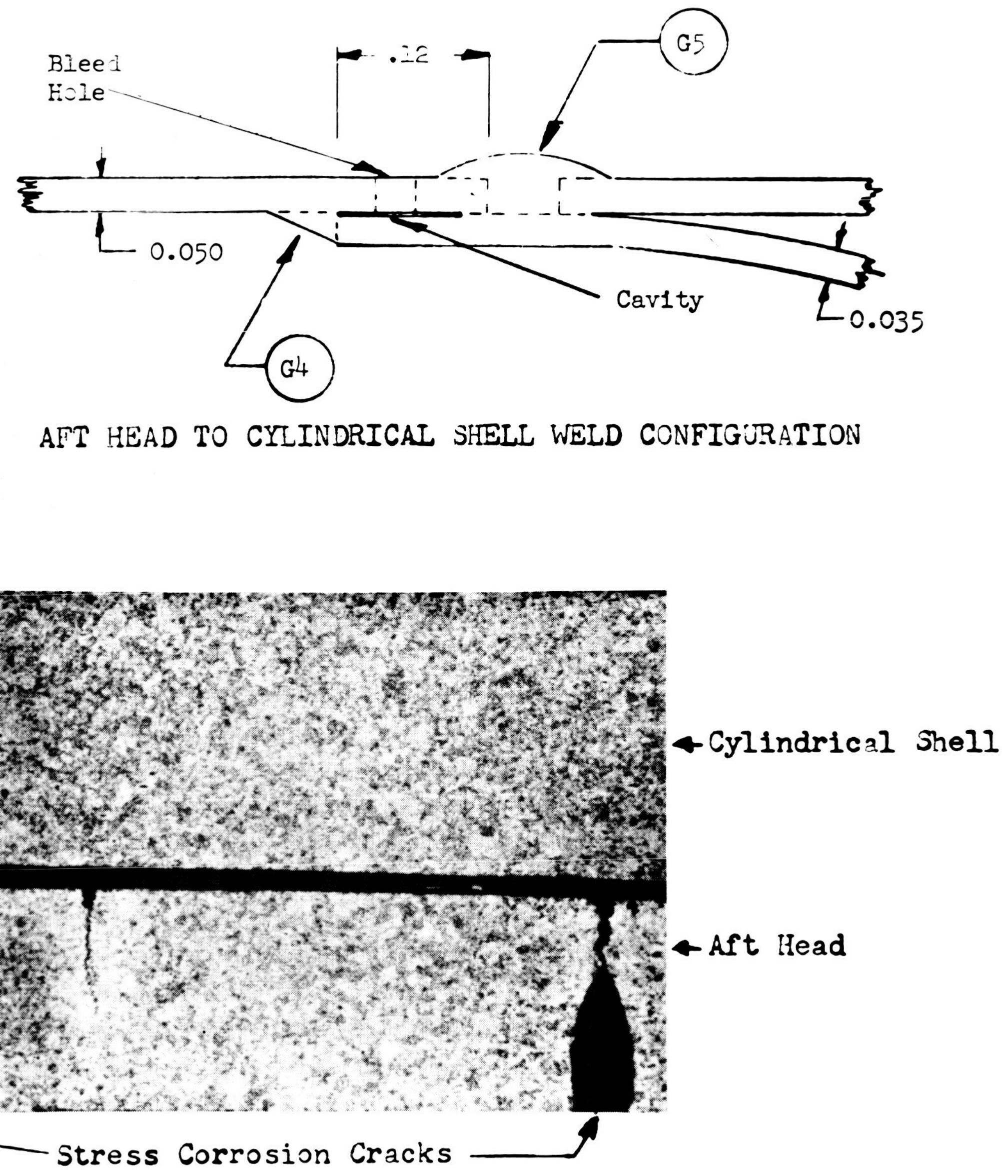


Figure 12. Geometry of head-to-shell weld joints (top) in type 410 stainless steel Aerobee rocket sustainer, and typical stress corrosion cracks (bottom) developed in the head.

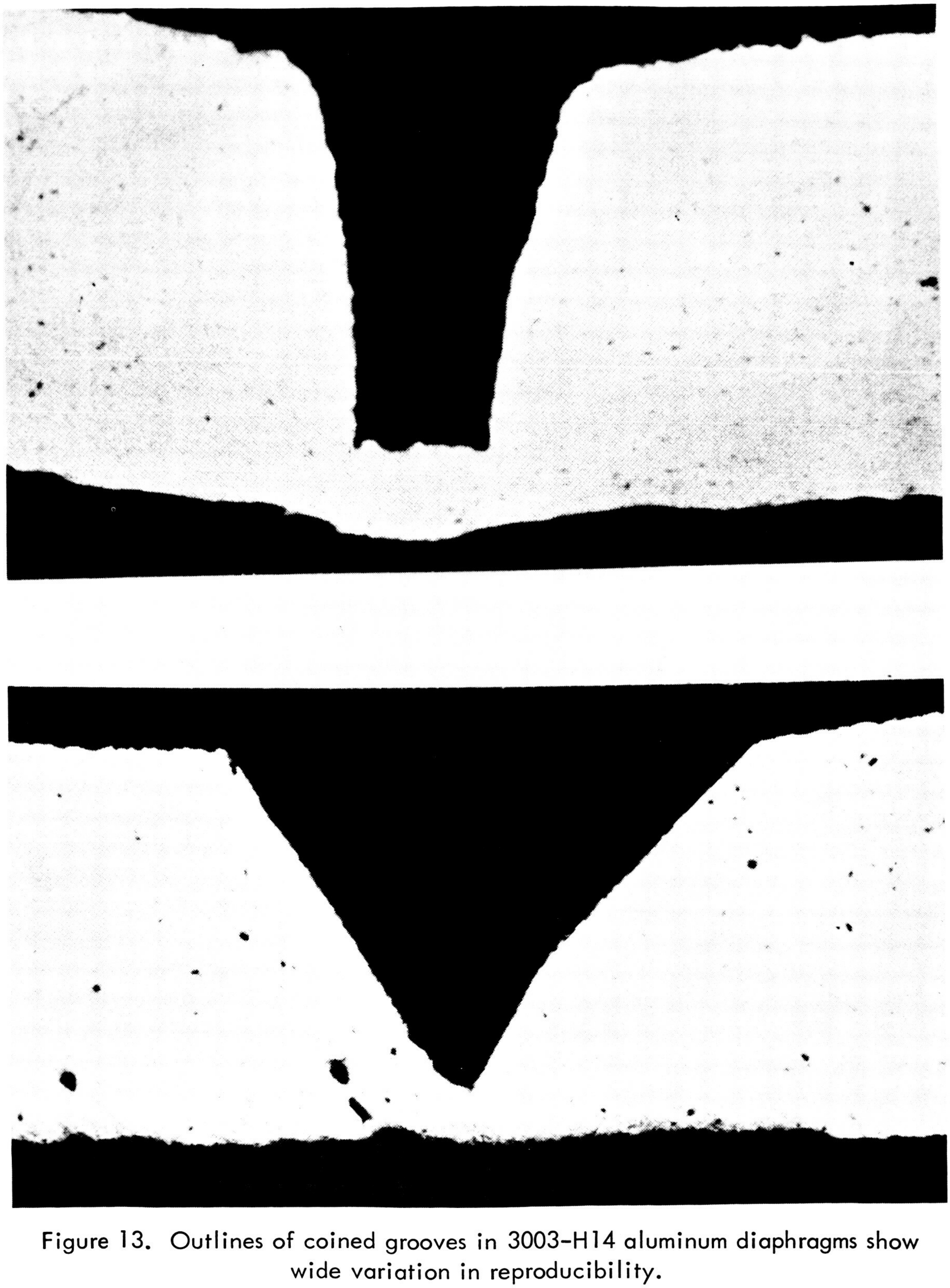


Figure 13. Outlines of coined grooves in 3003-H14 aluminum diaphragms show wide variation in reproducibility.