NON-DESTRUCTIVE INSPECTION OF TITANIUM JET ENGINE DISKS

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Pratt & Whitney Aircraft has incorporated titanium alloy for critical jet engine components for more than 15 years. The extensive service experience accumulated during this period has proved that strict material processing controls and inspections are necessary to insure material quality. A continued effort to improve both phases of the fabrication process has been required. In addition to the improvements in nondestructive inspection methods and process controls, a material record system has been established which permits tracing any parts complete history from the fabrication of the sponge to the finished engine component. This system has been instrumental in locating defective components with contaminated material. It has also been a tool for locating trouble spots in the fabricating process. When several components have the same defect they can usually be traced to one common operation. A detailed study can then be made of the operation and a rapid solution can be achieved.

Emphasis has been placed on the billet inspection in an attempt to eliminate unacceptable material before additional work is invested. With the recent use of titanium for airframes of military aircraft, there has been an even greater interest in this inspection phase by government agencies and airframe manufacturers. Because of the complex shapes of airframe components, the inspection of the finished product is difficult and a greater reliance must be placed on the billet inspection. In the case of jet engine disks, however, a more sensitive inspection can be performed on the individual component. At this time, thinner sections, better microstructures and larger surface areas are available. This is fortunate because the design criteria of the end use requires a much greater degree of inspection sensitivity than can presently be obtained in the billet inspection.

The vast majority of experience has been with the Ti-6Al-4V alloy, which has been used for jet engine compressor disks. Until recently this was the only alloy used for critical engine components. Although more recent engines have employed various other titanium alloys, the discussion presented in this paper will be limited to the 6-4 alloy.

The material defects encountered with this alloy can be separated into the following four categories: (a) Type I, interstitial segregation; (b) Type II, chemical segregation; (c) high density inclusions; and (d) clean porosity. The first three categories have been fairly well documented by several sources. The Type I defects occur as voids surrounded by interstitial stabilized alpha structures. They are characterized by an extremely high hardness of Rc 55 or greater. The occurrences are usually small, discrete areas that can occur anywhere within the part cross section. Because of the stress concentrations caused by the voids and the brittleness of the surrounding alpha structure, this defect is considered the most detrimental and cause for the greatest concern. An example of a Type I defect is shown in Figure 1. Type II defects, chemical segregation, are caused by incomplete alloying of the master alloy with the titanium. In a disk forging, this defect appears as streaks of either alpha or beta stabilized structure. Because of the amount of work from the melt to the forging, the streaks are usually quite long and always intersect the surface of the finished part. The alpha stabilized structure caused by aluminum-rich areas can be identified by its hardness which is slightly higher than that of the base metal but somewhat lower than that of the interstitial stabilized alpha. An example of aluminum alpha segregation is shown in Figure 2. High density inclusions are usually caused by foreign material in the melt. They have been routinely detected by radiography and are not presently considered a major problem in the 6-4 alloy. The fourth category, clean voids, has not been as well publicized, but defects of this type have been detected in disk forgings. Although this defect does not have the surrounding brittle material of a Type I defect, it can represent a significant stress concentration and is considered a serious defect. A typical void defect is shown in Figure 3.

Titanium jet engine compressor disks have been categorized as "thick disks" used for the fan stages or "thin disks" used for the higher stages. Because the large fan blades require larger load carrying ability, the fan disks have appreciably thicker web and bore sections. The smaller blades of the higher compressor stages have lesser requirements and the disks have much thinner sections, generally not exceeding half an inch. Because of the thin sections and the large surface-to-volume ratio, radiography and surface

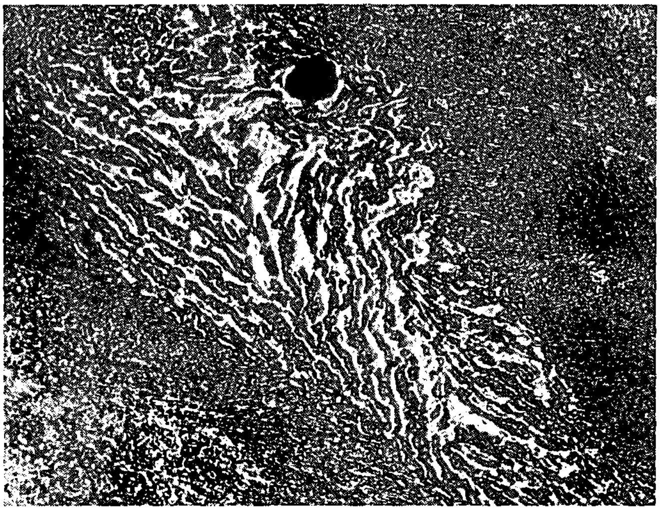

Figure 1

Type I Interstitial Segregation in 6-4 Alloy

Figure 2

Type II Chemical Segregation from an Aluminum-Rich Area in 6-4 Alloy

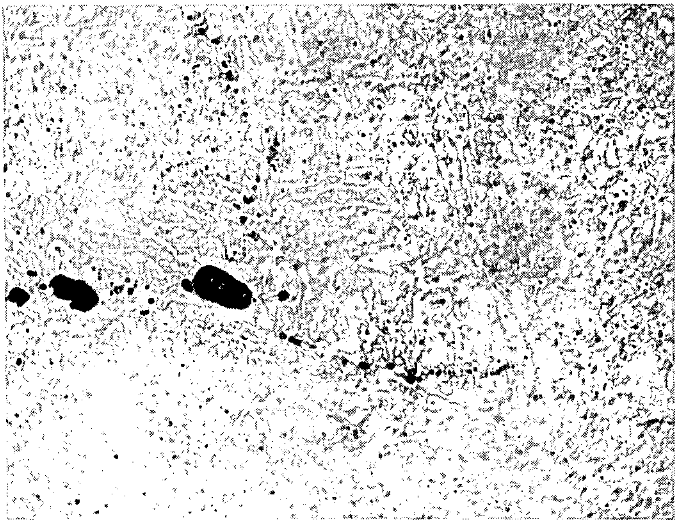

Figure 3

Clean Void Defect from Disk Forging

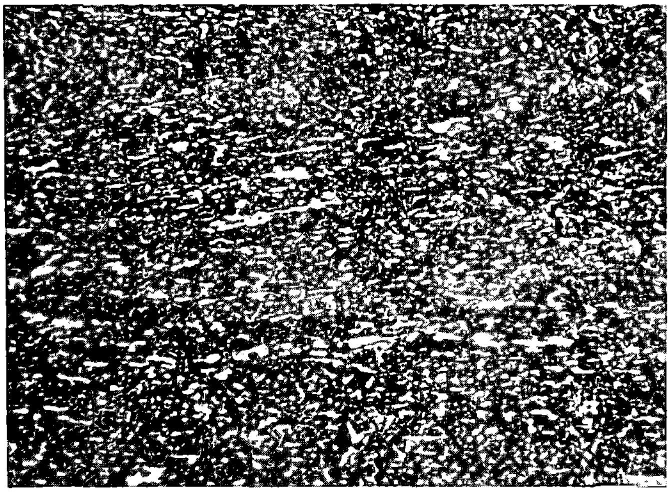

Figure 4

Microstructure resulting in Reject Signals in Production Ultrasonic Inspection. Evaluation with Focused Transducers Identified Area as Acceptable.

inspection methods have been adequate to insure quality on these thin disks. On thick fan disks, however, a major emphasis has been placed on ultrasonic inspection. For these disks, the forgings are machined to an ultrasonic inspection configuration (1S SHAPES) designed to create flat surfaces parallel to the plane of the disk. The flat surfaces permit undistorted sound entry perpendicular to the plane of the disk. Because the forging operation tends to make defects become planar in the plane of the disk, maximum detectability is obtained with sound transmission in this direction. The inspection is an immersed pulse echo method utilizing a 3/4-inch diameter 5MHZ lithium-sulfate transducer. Both broad band and tuned pulse ultrasonic units have been used. The present inspection level is approximately equal to the response of a #1 Flat Bottom Hole (.015" Dia.). To maintain this inspection level, it is necessary to control scanning speed, indexing and alarm systems to insure that random defects will not be missed because of insufficient response time or lack of signal amplitude. Setup procedures utilizing step blocks with flat bottom holes at varying metal travel distance have been established to obtain uniform distance-amplitude response and to verify front and rear face resolution. Because of resolution limitations, material near the surfaces is not inspectable. This is compensated for by allowing additional material in the inspection configuration which is removed during final machining. Scanning of each part is performed from each face and from the periphery to provide complete coverage and optimum orientation to non-planar defects. The largest source of problems in maintaining the inspection level has been random signals obtained from variable macro- and/or microstructures which are not necessarily detrimental to part operation. Because of these random signals, it has been necessary to develop methods of reviewing indications obtained during routine production inspection. The most successful method which is presently being applied utilizes focused transducers. By using focused transducers, a very small beam diameter is obtained and the random signals created by the accumulation of reflected energies from multiple grains are greatly diminished. Because more energy is concentrated on the small area of true defects, their signals become more prominent. The limited depth of field and small beam diameter make this method unattractive for part scanning but it has worked well for signal evaluation studies. Results have been verified by extensive metallography of many indications from production runs. An example of a microstructure that resulted in random signals identified with this method is shown in Figure 4. As evidenced by the defects detected, ultrasonics has been a viable tool in establishing disk quality. However, additional work is continuing to further improve inspection sensitivity, reliability and uniformity. Efforts are being made to establish equipment and transducer standardization; to obtain improved microstructures for greater sensitivity, and to establish improved inspection shapes.

The next step in the inspection process occurs when the disks, both thick and thin, are in a semi-finish machined condition. At this time, all finish machined dimensions are met, except that holes and blade slots have not been machined. This configuration provides the optimum condition for radiography. The thinnest sections are available with a minimum of loss due to film overexposure at part edges. Multiple exposures are taken to obtain better than a 2% penetrameter sensitivity at each disk thickness. This method has been extremely successful in detecting high density inclusions and voids. Because the maximum thickness in critical areas of thin disks is usually less than .500 inches, the method is very sensitive for the detection of Type I void defects and clean voids. To accomplish this sensitivity, a 250 or 300 KVP unit with a 900 to 1500 milliamp-sec exposure is used with Kodak M film processed in a Kodak automatic processor. The film is read on standard film viewers with up to 3X magnification for evaluation of individual indications.

After the parts have been finish machined, they are subjected to a new etch anodize procedure which was developed at Pratt & Whitney Aircraft as part of the search for improved titanium segregation detection methods. Previous etch anodize procedures utilized an anodize procedure which turned the material a gold color and was sensitive only to segregation of pure titanium. The new Blue Etch-Anodize technique consists of etching with an acid salt solution, anodizing in trisodium phosphate and partially stripping the oxide coating. In contrast to the gold procedure, this method will detect the following types of surface-connected alloy segregation:

- Aluminum-Stabilized Alpha Segregation - This appears as an irregular deep blue line with or without branches in a light blue background. A black and white photograph of a typical defect is shown in Figure 5. The true contrast is not appreciated without color but prominence of this defect with this method is evident.

- Type I Alpha Stabilized Segregation - This type also appears blue and must be differentiated from aluminum stabilized by its high hardness.

- Vanadium Stabilized Beta Segregation - This defect appears as lighter gray or white lines in a light blue background. It is associated with areas of aluminum stabilized alpha. An example of beta segregation is shown in Figure 6. Again this is a black and white photograph which is not indicative of the true color contrast.

- Chemically-Pure (CP) Titanium - This defect also appears as light gray or white and can only be separated from vaadium stabilized beta segregation with further testing.

Evaluation of this method on test samples has indicated stock loss-

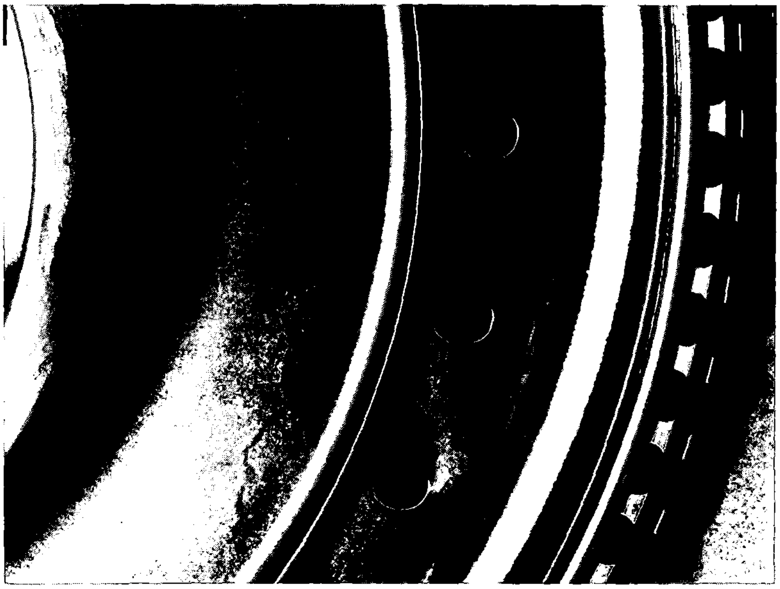

Fig. 5. Blue etch anodize indication of alpha stabilized structure in 6-4 alloy. Indication is deep blue on a light blue background. Note: Black and white photograph does not indicate full color contrast on actual part.

Fig. 6. Blue etch anodize indication of beta stabilized structure in 6-4 alloy. Indication is lighter gray on a light blue background. Note: Black and white photograph does not indicate full color contrast on actual part.

es from 0.000040" to 0.000063" which are considered to be insignificant. Results from bend, low-cycle fatigue, tensile, hydrogen embrittlement and microstructure tests indicate mechanical properties of Ti-6Al-4V material are not affected. This method is a real improvement in the detection of titanium segregation. Its use in production is continuing to reveal additional material defects previously unnoticed and a complete evaluation of the method can only be made after extended use. Details of the inspection procedures are given in Appendix A.

As a final inspection, engine disks are given a "spin fluorescent penetrant" inspection which consists of blading the disks and rotating them at engine speed in an evacuated chamber. While the disk is at speed, fluorescent penetrant is sprayed on all surfaces. The disk is then removed from the pit and examined with standard black light procedures. The object of the test is to create engine stresses within the disk to force substandard material to crack. It also induces a tensile stress which permits penetration of fluorescent penetrant fluid in cracks that would normally be too tight. Because of the brittle nature of Type I defects and the large surface-to-volume ratio, this method has been especially effective with thin disks.

With the high sensitivity levels of ultrasonics and radiography for subsurface defects, the much improved etch anodize procedure for all forms of surface connected segregation, and the dynamic fluorescent penetrant inspection for surface cracking, each disk component has been given a most thorough inspection before it is accepted.

APPENDIX A

DETAILS OF BLUE ETCH ANODIZE METHOD

Parts must be free of cleaning or buffing compounds and other foreign materials. Proper anodizing requires that the current fall to zero after the initial surge that takes place upon the application of the 30 v. Continued amperage indicates foreign material or unmasked protective coatings on the part and/or exposed metal other than titanium on the processing fixture. Any of these faults will result in an unsatisfactory blue color and a poor color contrast between normal material and the segregation.

All steel parts of anodizing fixtures should be masked with a hard permanent material, such as Microsol E1003. All identification markings must be masked with plastic tape to assure their retention.

The test comprises 15 steps, as follows:

1. Vapor degrease part.
2. Immerse part in heavy-duty alkali cleaner for 1 to 2 min. at 120 to 180°F.

3. Rinse part in clean cold water, and inspect for water breaks. Repeat cleaning and rinsing until part is clean.
4. Hang part on titanium alloy hook and immerse in agitated solution of a dry acid salt, such as MacDermid Metex Acid Salt M-629 (16 oz per gal), at room temperature for 1.5 min. Agitate part upon immersion.
5. Rinse etched part thoroughly in clean cold water, removing loosely adhering smut by pressure spraying (compressed air-water).
6. Attach anodizing fixture to part as quickly as possible with a minimum of handling.
7. Rinse fixtured part in clean cold water.
8. Immerse fixtured part in a 15 oz. per gal. solution of trisodium phosphate at 70 ± 10 F, agitating part upon immersion. Anodize at 30 v for 30 sec., being sure not to turn on the current until the part is completely immersed. Do not agitate fixtured part during anodizing.
9. Remove fixtured part and rinse in clean water.
10. Detach part from anodizing fixture, attach to a titanium alloy hook, and rinse in clean cold water. Avoid unnecessary handling.
11. Immerse part in aqueous nitric-hydrofluoric acid solution. Use 35% (by volume) technical grade nitric acid and 2.5% (by volume) technical grade hydrofluoric acid. The purpose of this step is to remove most of the blue color from the background to develop maximum color contrast between the segregation and the background. Immersion periods: Ti-6Al-4V, 2 to 10 sec.; Ti-8Al-1V-Mo, 15 to 25 sec.; and Ti-6Al-2Sn-4Zr-2Mo, 10 to 20 sec.
12. Remove part from acid, immerse in clean cold water as rapidly as possible and rinse thoroughly.
13. Rinse in hot water (190 to 210°F).
14. Blow dry with clean compressed air.
15. Inspect.

Processing tanks may be unlined, except for the two acid tanks which must be lined with rigid PVC or its equivalent. We recommend temperature indicators for the alkali cleaner, anodizing and hot water tanks. Mechanical stirrers are required in the alkali cleaner, both acid tanks and the anodizing tank. The rinse tank adjacent to the dry acid salt tank must have pressure spraying equipment, and timers are used on both acid tanks and the anodizing tank.

The rectifier must be rated at a maximum of 6% ripple at 30 v, no load. It should also allow the voltage to be raised to 30 v rapidly (1 to 3 sec.), preferably with automatic control. Finally, the rectifier should have a time-actuated switch which will cut out a 1.2 ohm resistor (installed in series with the load) after 3 sec. This resistor limits the initial surge of current, reducing chances of arcing.