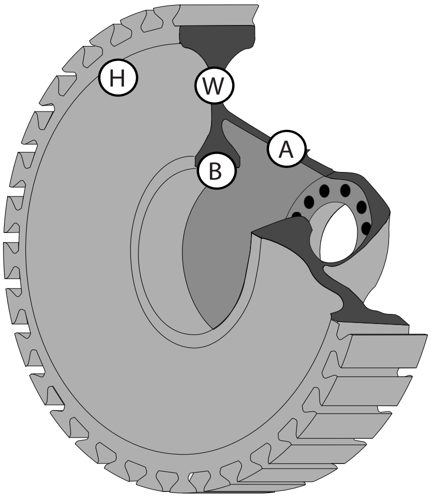
Flaw distribution in titanium rotor disks:

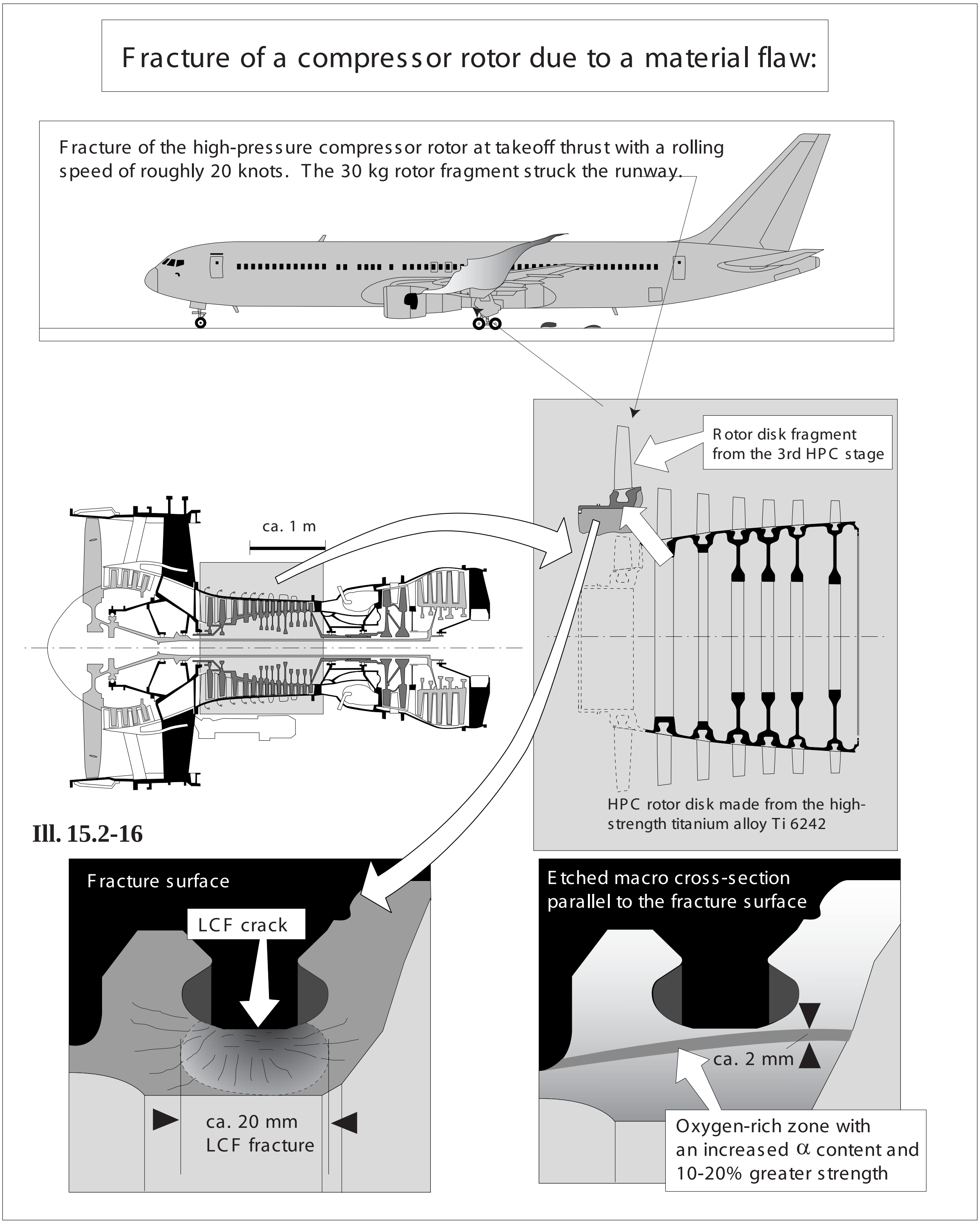


Damage \ Flaw location	B Hub bore	W Web	H Bore in the disk ("web hole")	A Arm for fastening or spacers
Rotor disks with flaws				
Cracked rotor disks				0
Burst rotor disks				0

Ill. 15.2-15

Illustration 15.2-15 *(Ref. 15.2-30): The analysis of* ***flaws in rotor parts made from a titanium alloy*** *in the time period before 1990 resulted in the following conclusion: the frequency of flaws from the melting process (Ill. 15.1-12) and the forging process (Ills. 15.3-12 and 15.3-13) is not equal throughout the entire part volume. One can see that* ***dangerous flaws*** *occurred, or at least were discovered,* ***especially in the hub area.*** *This type of flaw distribution is also valid for Ni-based alloys and high-alloy steels produced in similar processes. Flaws in the hub area are especially relevant to safety. This area is typically subject to very powerful cyclical loads. In addition, in the thick hub cross-sections, it is more difficult to realize the plastic deformations during forging that are required to achieve the necessary strength properties (Ills. 15.1-14 and 15.2-11). This* ***deformation is a prerequisite for the smashing of flaws (impurities, also see Ill. 15.1-16) and/ or giving them a favorable orientation relative to the main load direction*** *(Ill. 15.1-13). If the deformation is not sufficient, larger flaws in more effective positions are more likely. About 80% of the burst rotors had* ***crack initiation weak points below the surface.*** *The LCF cracks grew towards the surface. This meant that dangerously large cracks could only be detected at an advanced stage through penetrant testing. Of course, it was a prerequisite that this type of testing occurred during this growth phase of the cracks, such as during overhauls.*

Generally, it can be said that the ***probability of material flaws increases along with the volume of the parts****, i.e with the thickness of the cross-sections.*



Ill. 15.2-16

***Illustration 15.2-16** (Ref. 15.2-18, Example 15.2-3): The one-piece compressor rotor (spool) made from the high-strength titanium alloy Ti6242 failed between the third and ninth stages (middle right diagram) due to LCF (bottom left diagram). The crack was traced back to a decrease in dynamic strength in the area of an oxygen accumulation (segregation, bottom right diagram) with an increased proportion of α-structure. The flaw area had a slightly higher hardness of R_C. 38-43 relative to the matrix*

hardness of R_C 34. This was most likely a ***Type II, Category 3*** *flaw (Ill. 15.2-14). The weak point was near the highly-stressed circumferential dove-tail groove.*
The ***oxygen accumulation occured during the triple remelting process.*** *A possible cause was a pronounced* ***vacuum loss*** *during the second remelting process. This occurrence could be reconstructed with the aid of the required documented* ***process records*** *(Ill. 15.3-10). It is rare for such a process to occur with unallowable intensity. It occurs when the electrode shifts to a* ***cooling water leak in the mold.*** *However, the pressure increase was still within the limits that were tolerable at the time the raw material was produced (1972). The oxygen from the water, which dissociated at the high temperature, then diffuses into the melt bath (Ill. 15.2-17).*
Typical characteristics of such a procedural deviation were attributed to the damaged part. This made it possible to identify other potentially threatened parts that were ***located near the damaged part*** *in the casting block (also see Ill.15.2-22). In compliance with the demands of the responsible authorities, all suspect parts (21) were removed within 30 days.*

This type of weak point with no cracking could evidently not be found through ***ultrasonic testing due to its unique location.*** *The flaw, insofar as it spread to the surface, would have been detectable with the aid of macro-etching (****blue etch anodizing = BEA****). However, this process was not yet in use at the time.*
*Even in the finished part with potential cracking, ultrasonic testing during an overhaul or inspection was problematic. The flaws in the groove area were in a location that was most unfavorable for ultrasonic testing (****blind spot****). This is especially true of cracks that are located directly below the surface. During the last overhaul, ultrasonic testing showed anomalous findings, but they were categorized as allowable in accordance with regulations.*
For this reason, ***additional eddy-current testing*** *was recommended for the detection of cracks near the surface.*

Example 15.2-3 (Ill. 15.2-16, Ref.15.2-18)

Excerpt: "...Shortly after the commencement of the take-off roll, at about 20 knots, there was a loud explosion and the aircraft yawed sharply to the left. The takeoff was rejected, and there was a fire warning on the left engine...
Approximately **30 kilograms of rotating hardware** from the left engine HPC and the compressor case was found on the ground near the aircraft. No engine debris penetrated the passenger cabin...
The engine's inlet gearbox was fractured, causing a disconnect of the engine accessory drive, which includes the main engine fuel pump...
The uncontained failure of the third stage of the 3-9 high-pressure compressor spool was due to the presence of an **oxygen rich segregate**..."

Comments: Several similar damages in the same engine types/rotor design have been reported over a longer time period. Evidently, in all cases, LCF cracks originated in **material flaws** following cyclical loads from the startup/shutdown cycles. The problems seem to lie in the quality assurance of the raw part production for **large titanium rotors with thick cross-sections.** As far as one can tell, this type of problem cannot be completely ruled out in other engine types even today.