Focussed on: Fracture and Structural Integrity related Issues

In-service fatigue cracking of the propeller shafts joined by a spline-pinned construction to the engines of AN-24, AN-26, and IL-18 aircrafts

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ABSTRACT. The paper delivers a critical review of the research data on the crack initiation and crack growth patterns characteristic of the components of the spline-bolted joints between the propeller shaft and reducer shaft at An-24, An-26, and Il-18 aircrafts. Cracks in the shafts nucleated because of reduced bolt-fastening force. Actually, the bolt (bolts) failed first (also by fatigue) and then fatigue cracks nucleated and grew in the shafts, the spline surface fretting zones and/or sharp edges of the attachment (bolt-conducting) holes making the crack origin sites. The crack growth history shows itself through the regular Macro-Beach Marks, each mark sequentially pointing to the next loading event of the propeller shaft, i.e., to each next flight. The cracks cease growing for some while in the airscrews and their shafts just replaced to another aircraft. For the airscrew shafts, the critically assessed data show the crack growth period Np ranging as five to ten percent of a total running period N_f. We recommend performing nondestructive inspection of the airscrew shafts on every 250-hour running period to ensure the safety flights.

KEYWORDS. Propeller shaft; Fatigue; Spline-bolted joint; Fractography; Crack-growth period.

INTRODUCTION

At the stresses reduced to the level typical of high-cycle fatigue (HCF) behavior, the structure components exhibit lowered ratios N_p/N_f between their crack growth period Np and total duration N_f of cyclic loading [1]. So, near the stress levels low as the so-called fatigue limit, the (N_p/N_f) magnitudes can range as 0.05 to 0.1 for a smooth-surface test body. The (N_p/N_f) data scatter primarily in response to the stress concentration effects peculiar to the free surface of a structure component. An N_p/N_f magnitude can increase, typical of the contacting components of structure joints that additionally suffer surface damage from wear, and, thus, exceed the magnitude peculiar to a stationary loading regime free of a surface damage.

As regards the propeller shafts (PS) of AI-24 and AI24VT engines of AN-24, AN-26, AND IL-18 aircrafts, cracks nucleated and grew—at the HCF or ultra-high cycle fatigue (UHCF) regimes (for the durations of 10^8 – 10^9 loading cycles [2–4])—from spline fretted sites, from sharp edges, or from material defects in a shorter spline area. In some cases, crack propagation terminated at the complete separation of the PS from a still operating engine, Fig. 1. Though the aircraft did land successfully this time, an urgent problem arose to reveal why the cracks generation occurred and to program reasonably periodic in-service inspection of the PS items to prevent, thereby, the in-flight cases of broken away PS.

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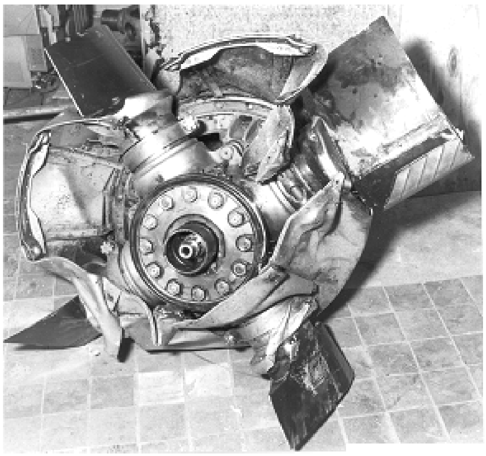

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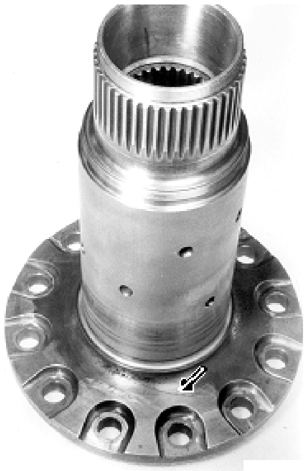

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Figure 1: (a) The AN-24 aircraft wing (general view) in the braking zone of the propeller shaft; (b) a fraction divided by braking from the propeller shaft; (c) the view of the propeller shaft with a fatigue crack (pointed to by arrow).

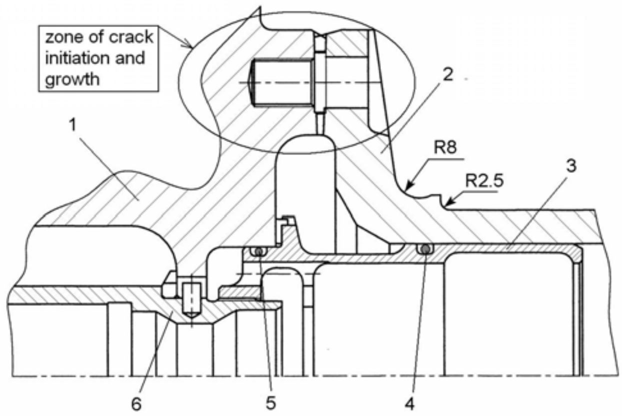
We mentioned above that, in a PS case, one should relate estimations of the N_p/N_f magnitude to the HCF-to-UHCF transition range and to N_p/N_f varying as 5 to 10%. Such an approach appears realistic as confirmed by the N_p/N_f estimations done for the cracks that grew from the surface damage sites in gear wheels [5]. Yet one still wants to ascertain which of the two cases -unsatisfactorily tightened bolts or locally overstressed (beyond a limiting state in above-mentioned zones) joint-structure components- dominates as the cause of the spline joints failure.

Below we critically assess the data (of more than 40-year period research) on the patterns and various causes of the in-service propagation of fatigue cracks in the airscrew shafts of AI-24 and AI24-VT engines on IL-18, AN-24, and AN-26 aircrafts [2–4].

INFORMATION ON THE CRACKS AND FAILURES OF PROPELLER SHAFTS

They use a spline-bolted joint to have a propeller hub fasten to the propeller shaft of an AI-24 engine (Fig. 2). The splined flange portion of an PS experiences dynamically applied loads that cause fretting over the spline surface. Cracks became visible in the PS of AI-24 engines almost as early as at the very beginning period of running the engine.

The first two PS exhibited many a cracked spline on the first 500 and 300 hours of running. Those cracks were of fatigue nature, started propagating from fretting-corrosion zones and grew as far as for 2/3 spline length at the smaller-modulus side. Nevertheless, even having inspections repeatedly and frequently performed (see Fig. 2), with the magnetic inspection included, one remained unable to guarantee against in-service crack growth likely to bring the PS about failure (see Fig. 1a).



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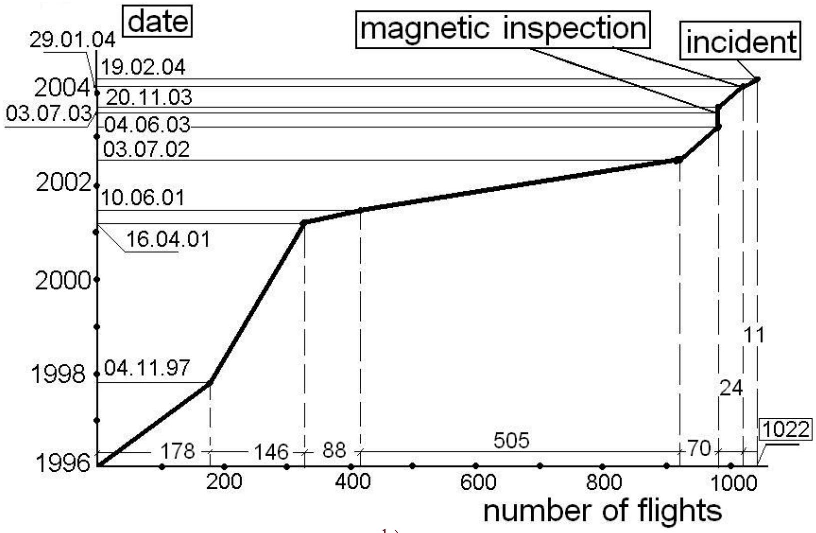

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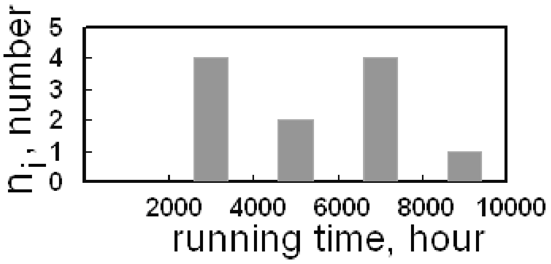
Figure 2: (a) The joint (schematic) of the (1) propeller hub and (2) propeller shaft; (3) to (6) internal parts with (4 and 5) the sealing caps; (b) the sequences and durations of running periods; one can also see, at the ordinate, the dates and periodicity of inspecting the PS torn out in flight (see in Fig. 1a).

Cracking took place either because of having the nuts (fastening the propeller) tightened unequally or as caused by the dynamic loadings (born by excessive misbalance). Effects of the said loadings revealed themselves in the propeller obliquely blown–up in flight. When insufficiently tightened, the PS flange experience tiny shifts and, consequently, local fretting-corrosion and cracking of splines occurs over their contacting areas. Experimental investigations of the dynamic stress patterns in the elements of a splined joint of an AV-72 airscrew shaft with an AI-24A engine shaft revealed the following. With the fastening nuts tightened uniformly, the level of the stresses (tensile component) applied dynamically to the fillet part of an PS remains insensitive to the momentum of tightening (in 9 to 18 kgm range) of the pin nuts pressing to one another the flanged portion and the body of an PS. Having reduced the tightening momentum from 13 to 9 kgm does not reduce the stresses in the PS fillet portion. In-service inspections of PS-to-engine junctions confirmed stability of the tightening momentums of the nuts fastening the AV-72 PS units to the AI-24 engine shafts.

The cases of broken pins belonging to the splined joints ceased owing to the constructional improvements that brought about greater fatigue resistance of the pins, stronger tightening of PS to its hub, as well as greater total rigidity of the splined junction itself. Zones of extensively fretted splines shifted from the miner-module area to the middle part—between the pinholes. Nevertheless, statistically and regarding an equal running time, the PS units of an AI-24 (two series) engine, screened out on repairs in 2001 to 2003 years, showed that the above constructional improvements did not alter the cracking trends as compared with those of the ASS unites screened out in 1977 (Fig. 3).



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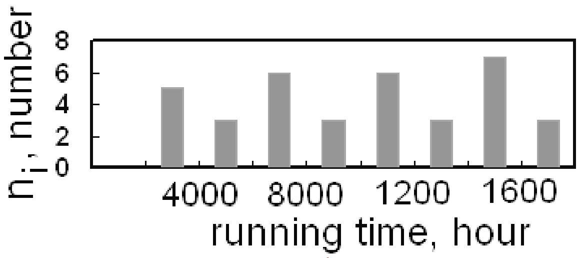

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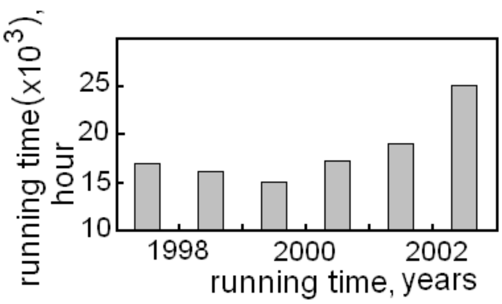
Figure 3: PS rejected out of the service in (a) 1977 and (b) 2001, 2002, and 2003 (statistical data).

The greatest stress - 175 MPa (average for various frights) - achieved by dynamic loading and measured by experiment in the R = 8 mm fillet part - approaches the bifurcation point-fatigue limit - for a fatigue life of 10^7 loading cycles. This case is closely reproducing an in-service state of the most stressed PS when executing, landed, a nonstandard abrupt turn by 90^o in a two- to three-seconds time. However, only two PS unites broke over the R = 8 mm fillet zone in service (see Fig. 3) after the most extensive cracking after the 3000- to 6000-h operation.

Despite the thorough screening out of the cracked PS conducted on repairs or in service, several cases of PS broken away in flight still took place. One of the incidents occurred with an AN-26 No. 26582 AK aircraft, named Irbis, which belonged to Kazakhstan: on April 04, 2004, an PS broke out of the right engine and hit the plane cabin, which caused decompression and forced landing. On the strength of this in-service incident of a broken PS, they took up again regular magnetic inspections of these structure components. Another breakdown incident with an PS (AN-26RV RA-4628 aircraft) inspired, in February of the same year, inspection of 18 PS units (already inspected once earlier) of which six units exhibited cracks. Next to the first inspection, the PS running time continued to 977 h … 1158 h and to 286 h … 811 h for the AN-24 and AN-26 aircrafts, respectively. The second inspection done 286 h past the previous one showed that this running time was long enough for the cracks in the PS to extend by another 12 mm.



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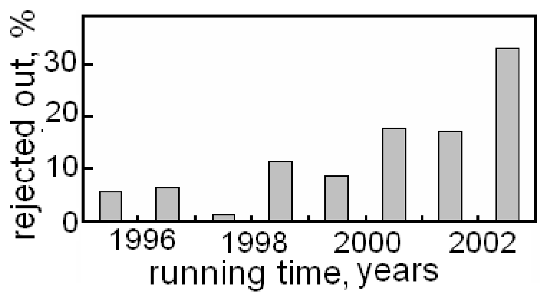

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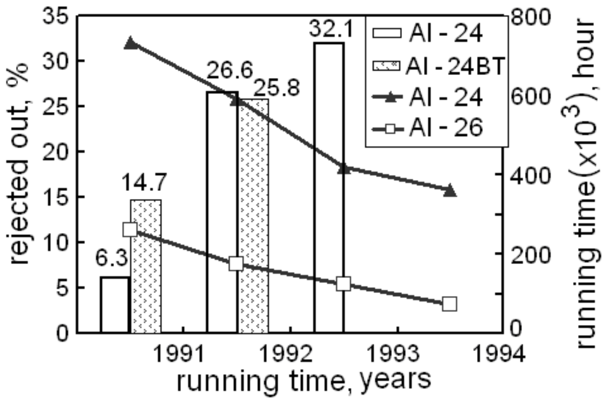

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Figure 4: (a) The running time and (b) percent of rejected out PS, respectively, for an AN-26 aircraft; (c) a similar histogram for the rejected out PS, with the superimposed curves of their running times for different engines.

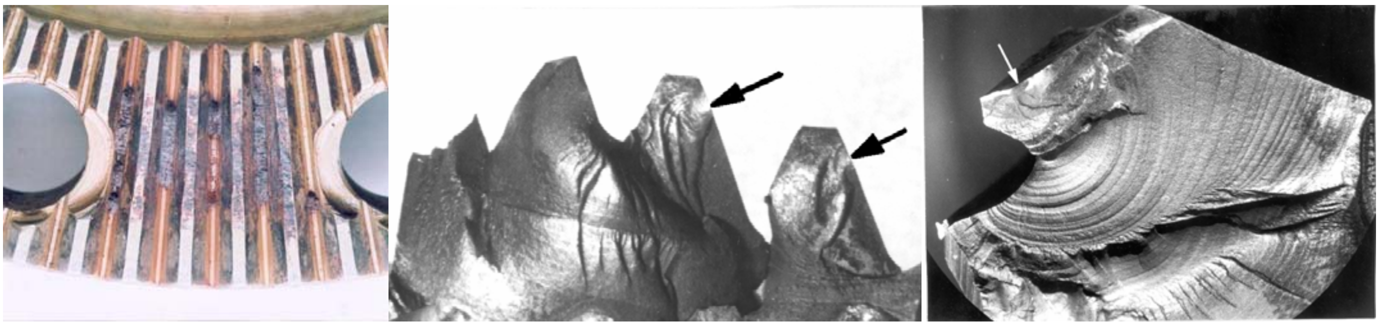
In the following years, inspection for cracking at the repairing plants brought about greater amounts of the sorted out PS articles (from 8.8% in 2001 to 41.8% in 2003). The most numerous of the sorted out were the articles run for 2000 to 4000 h on AI-24VT engines. No data are available regarding a peak percent of the shafts screened out of the engines AI-24VT, Series 2. One can expect such a peculiarity as long as the type AI-24VT engine differs from type AI-24, Series 2, engine in the strength of a combined effect that the loading conditions have on an PS. If one replaces arbitrarily an PS between the two engine types, he alters in the opposite direction the running duration required to initiate fatigue cracking. So having moved an PS from an AI-24, Series 2 to an AI-24VT engine brings about longer running time (4000…6000 h) to initiate fatigue cracks, whereas the opposite change of the running time (to 2000…4000 h) is the case for having the PS moved in the reversed direction—to an AI-24, Series 2 engine.

Having analyzed the screening trends of PS on repairs revealed that the numbers of fatigue cracks increased in the PS from AI-24 engines. Such an increase occurs owing to the more extensive employment of AN-26 aircrafts that, though at the ordinary service regimes, bring the greatest damage in the splined joints. Such a view follows from the statistical data acquired since1996 and compared with those acquired earlier - between the 1991 and 1993 (Fig. 4) - on the screening intensity of PS for the sake of cracks.

In the earlier period, the share of the PS screened out at repairs increased from 6.3 to 32.1% despite the prominently reduced total running period of the An-24 and An-26 aircrafts. By 1993, the share of the PS screened out at repairs exceeded 30%; nevertheless, in that year the first case of an airscrew shaft broken out in flight took place. That share also exceeded 30% in 2003 and, again, the airscrews torn out in flight showed themselves on (year 2003) An24RB RA-46828, (year 2004) An-26 RA-26552, and (year 2004) An-26 RA-26582 aircrafts. At last, late in 2004, a through crack showed itself in the fillet part (R = 8 mm) by oil leak and increased shaking of the plane in flight. They only had two flights to perform until the full separation of the shaft!

CHARACTERISTIC PATTERNS OF INITIATING AND GROWING CRACKS

Cracking begins from a spline surface in the fretting-corrosion area or, otherwise, form a conjugation edge (corner) between the surfaces of a shorter spline and a pinhole. Crack initiation in a fretting-corrosion site shows that the shaft material behavior is characteristic of a partially closed synergetic system (Fig. 5). Crack initiation at the corner is largely relevant to the behavior of an open synergetic system (Fig. 6).

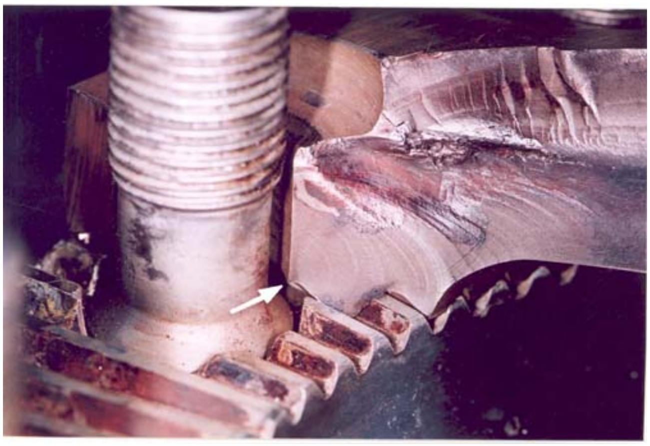


a) b) c)

Figure 5: (a) a spline rim (general view) with the spline sites of the fretting damage; (b) the fractures (open cracks) initiated at the fretting sites (pointed to by arrows); (c) the main fatigue fracture surface with Macro-Beach-Marks of the propeller shaft, with the crack origin site (shown by arrow) at a fretting spot.

Nevertheless, fractographically, the crack origin site at the corner showed the crack focus situated at some distance from the metal surface—under a sort of beading—a burr formed due to the pinhole machining. An important finding was that in some instances of breaking PS by growing fatigue cracks the latter grew concurrently from the damage (fretting) sites of spline surface and from the edge corners of the pinholes (Fig. 7).

From the origin sites of both kinds, the cracks grew leaving behind the patches of the macroscopic lines (Macro-Beach-Marks) of fatigue fracture. On the fracture surface, each of the single macroscopic fatigue lines is representative of a single flight cycle (FC) [2]. At the early stage—not far from the fracture origin site—the cracks propagate slowly. They grow, cutting the pinhole surface as well as the spline surface until they hit the rounded zone of transition to the internal butt-end surface of an PS.



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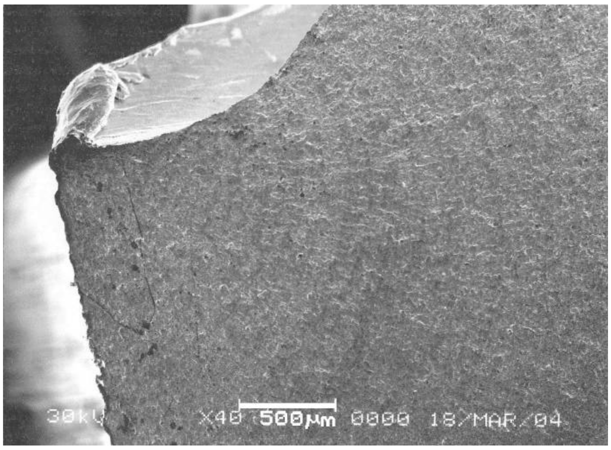

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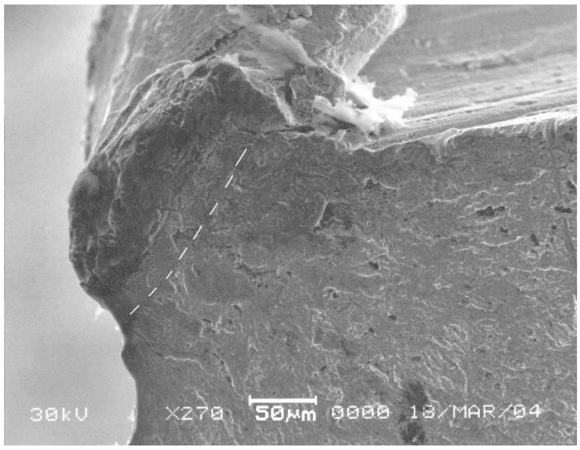

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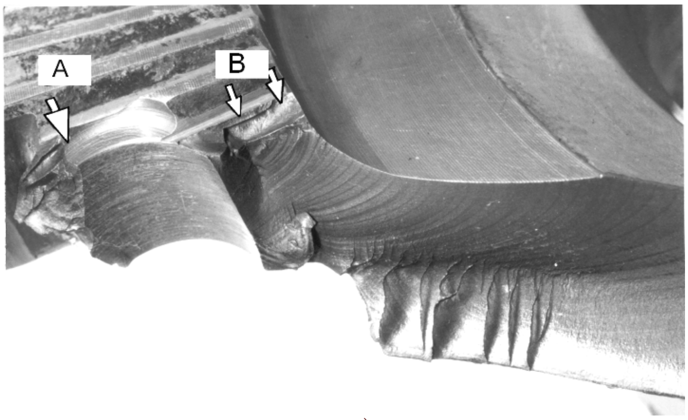
Figure 6: (a) The fracture surface (general view) of the broken shaft with the crack origin site at the pinhole edge (pointed to by arrow); (b) the fracture morphology by the crack origin site; (c) the crack initiation zone at the pinhole edge under the work-hardened (by drilling) surface layer of the shaft material. The dashed line divides the work-hardened zone from all the other parts of the fracture area.

A line spacing increases monotonically (see Fig. 6) toward the place in which the crack front changes for a new propagation plane. The crack growth period can last to 200 flight cycles at this stage.

Quite often, such a crack can show its farther propagation behavior as drastically transformed as much the reinstallation of airscrew violated the stress state of the PS joint. The engines vary in the stress pattern of an airscrew; so, having reinstalled an airscrew from other engine, one can expect nonlinear transient effects of building up damage in the shaft material. Consequently, crack propagation can slow down for some time (several tens flights) required for having formed a ledge, characteristic of the transition between different loading routines. Next to such a transient period, crack propagation accelerates and can bring about a failure as soon as in several flights.

At a rotation rate of 1247 rev/min, an PS experiences (2.25–5) x 10^8 loading cycles in its 3000 to 6000-h running period. So mostly, the actual operation conditions conform to the revealed level of stress applied to the fillet part of an PS. Such a view proves realistic as conforming to the actual PS operating periods. The latter appear 50-times over the figure 10^7—the number of loading cycles designed for the shaft material under the fatigue-limit stress. The cases of PS with fatigue cracks formed at the above operation times have nothing in common with off-design loading regimes. Fatigue cracks initiated in the range of UHCF is a normal effect, peculiar to the construction under a standard operating regime; the cracks form, once the material achieves its limiting state in the spline fretting zones and at the acute edges or at the material defects in the area of shorter splines. At a nominal applied stress, the mentioned PS zones experience stresses raised (concentrated) to a level that, at the mentioned above operating times, is creative of fatigue cracks. In the mentioned above range of running times and with the characteristic effects of fretting damage and high enough cyclically applied loads, the operating conditions of the splined joints appear creative of the cracks even if having removed acute edges (reduced local stress concentrations) and excluded press forming defects. A cyclically loaded airscrew shaft can exchange energy with the environment through its free spline surface; thereby, at a standard stress level, the PS experiences a surface damage that is more extensive than is the damage creative—after a longer running time—of a crack without the energy exchange (most likely under the surface of the most severely loaded zone). The other stress raising areas—at the pinhole edges or spline-material defects—are the sites of locally overstressed material, equally susceptible to cracking in their own locations zones.



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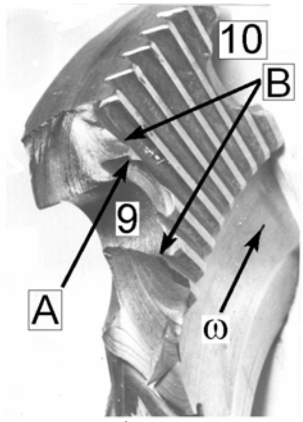

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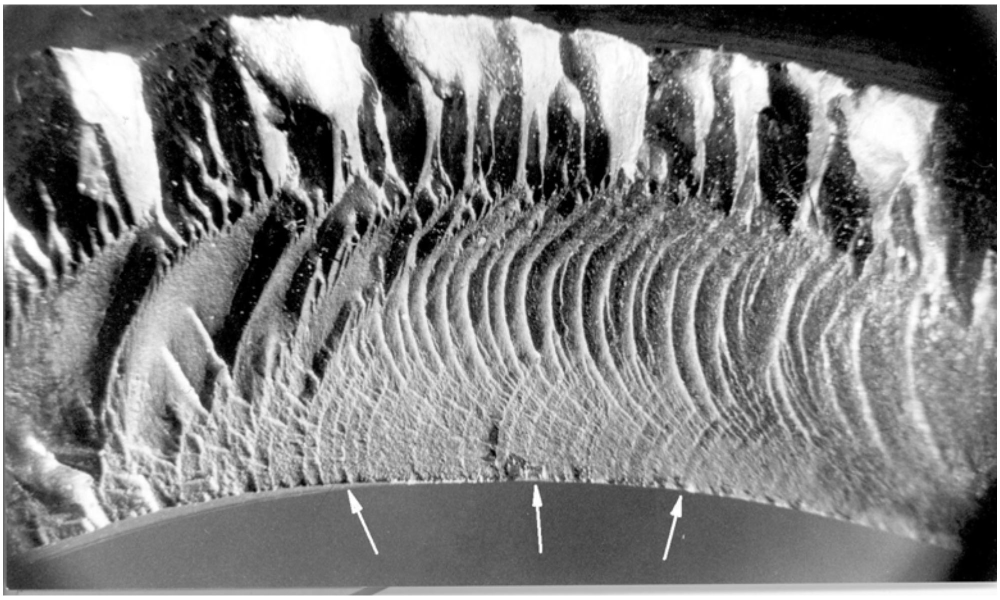

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Figure 6: (a) and (b) the crack origin zones (general view) of the fracture surfaces of two different PS; cracks nucleated at a pinhole edge (pointed to by arrows A and at the fretting zones of splines (pointed to by arrows B; (c) magnified view a portion of fracture surface showing the mesoscopic lines of fatigue fracture (pointed out by several arrows). Owing to a torque effect, the crack growth direction turned upward (see at the bottom part the group of fatigue lines crossing the lines of the other group)—to the external surface of the PS.

RELATION OF THE N_P/N_F RATIO TO THE INSPECTION PERIODICITY OF OPERATING PS

We mentioned above, that, , using a ratio N_p/N_f of 5 to 10% was the only way to calculate the crack growth duration in an PS as long as no data on the actual time to crack initiation were available. We applied such a ratio to the cases of cracks, initiated at various stress raisers—fretting zones, acute edges, and material defects—but never grown to their critical size.

We also took into account the forced (for various reasons) disconnections of an airscrew and of its reinstallation at other aircraft, which had its effect on the crack-growth behavior. Such a replacement of an airscrew can result in a long-term arrest or deceleration of the crack growth. Therefore, those increments in the operating time of PS supplied us with correction figures to the calculated N_p/N_f magnitudes.
The carefully examined patters formed by the macroscopic lines (Macro-Beach-Marks) of fatigue fracture made it possible to estimate the relative duration of fail-safety operation (durability) of the shafts. In case that, for various objective reasons, necessary information was lacking, we employed the ratio N_p/N_f of 5 to 10% to have acquired the estimations of the relative durability by calculations. Those estimations showed such a share of a crack growth period in the total running time of an PS as being reasonable and worth using.
Fractographically, early crack growth periods appeared to share 7.1 or 8.1 percent of the intermediate running time—up to the first violation of the crack growth pattern, caused by the first PS reinstallation, and the shaft No. 1456e exhibited (also by the first violation point of the crack growth pattern) a relative durability of 9.9%. Our calculations show these ideas to agree completely with the operation history of the PS. At the intermediate (between the PS installation events) stages of running which do involve crack propagation, the relative durability of PS can vary as 22 to 100 per cent, depending on whether the crack retardation effects do (22%) or do not take place. At a single running stage (No. 1109e shaft), which showed both fatigue fracture and a crack retardation effect, the relative durability achieved 7.25%; subsequently, the crack continued growing to cut through.
The growth rate of fatigue cracks in PS, calculated based on the spacing of fatigue MBM, was twice as high in the PS of AI-24VT engines as of AI-24, Series 2 engines. This finding indicates that the PS are more extensively loaded on the AI-VT engines and confirms that the above transient effects of crack retardation do show themselves when having the PS reinstalled from an AI-24VT to AI-24, Series 2 engine. Therefore, the earlier recommended 500-h periodicity of inspection appears only efficient for the AI-24, Series 2 engines. The PS of AI-24BT engines, however, can fail before its next standard inspection time, be a crack overlooked in a repair or in periodic inspection.
Statistical data on screening out PS (see Figs. 3 and 4) indicate that, notwithstanding the three stress raiser phenomena present, one should regard the cracking effects in PS as being a consequence of imperfect designing. The actual operating regimes, materials quality, pinholes geometry, and the contact characteristics of the splined joint—all accepted by the designer—concurrently contribute to the imperfection manifesting insufficient fatigue resistance of the construction. Compared with the acute edges, the fretting areas of the spline surface do not so efficiently shorten the initiation period of fatigue cracks. Only if we completely prevent the energy exchange of the shaft surface and environment, and, thereby, shift the crack origin site to the subsurface regions in the most highly stressed part of the shaft, a significant lengthening of the lifetime can occur. Practically, however, such a reconstruction of the joining, employed in its present design for transmitting a torque, appears hardly possible.
For that reason and according to the above discussion, the safety operation of an PS – AI-24VN engine assembly, in its present design, is possible providing a nondestructive inspection occurs after every 250 hours of the operating period. Thereby, a small crack, even if unnoticed by an inspector, will not achieve its critical length but become definitely detectable by the time of the next nondestructive inspection.

CONCLUSION

1. Owing to the special characteristics of their present design, the spline-bolted joints between the propeller and reducer shafts of an AI-24 engine remain unsafe from the in-service initiation and propagation of fatigue cracks.
2. In the components of a spline-bolted joint, a crack nucleates owing to the (1) lost tension and to fatigue failure of the fastening bolts, (2) fretting corrosion of the spline surface, which makes a crack-origin site, and (3) the sharp edge of a pinhole. Cracks can form concurrently at both the fretting spot and the acute edge.
3. The ratio N_p/N_f for the periods of crack growth and propeller operation (durability) ranges as 5 to 10%; as regards the examined components of spline-bolted joint in that fatigue cracks nucleated in and propagated from various crack-origin sites; this ratio also holds in case that the crack ceases growing for a while on having the propeller assembly replaced to another engine.
4. Having acquired the period of crack growth in the propeller shafts from the number of Macro-Beach-Marks on the fracture surface made it approved to perform nondestructive in-service inspection of the shafts after each of the 250-h running periods.

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