An Assessment of the Controllability of the Main Parts of Aircraft Engines During Capillary Non-destructive Testing

O G Ospennikova¹, I I Kudinov¹, A N Golovkov¹, A S Generalov¹ and D S Skorobogatko¹

¹All-Russian Research Institute of Aviation Materials, Moscow, 105005, Russian

E-mail: viamlab622@gmail.ru

Abstract. The aim of this paper is to determine uncontrolled zones in the main parts of aircraft engines during capillary control using a luminescent set of flaw detection materials LYUМ1-OV. The main factors affecting the defect detection process have been described. The approach not previously used in the practice of aviation enterprises has been experimentally tested. This approach takes into account the quality of applying a film-forming developer to various surfaces of structural elements of aircraft parts, using luminescence brightness samples. The research has clearly shown the control zones of holes of different diameters and herringbone type locks of different widths. It is established that the data presented in literature sources of technical and technological documentation on the controllability of holes and herringbone type locks differs from the experimental data.

1. Introduction

During the certification of international and domestic aviation engines, the use of modern approaches is ensured in order to calculate the resource of main engine parts (MP) taking into account not only the non-strength characteristics of materials, but also the size of defects missed after non-destructive testing (NDT), both in the production process and during service period control [1-3]. The initial data for such calculations is the parameters of the probability of defects detection obtained from the results of certifying the system and technology of non-destructive testing. In the domestic aviation engine building industry certification procedure of the NDT of MP is carried out in accordance with OST (Standart) 1 01207 [4], namely after conducting general, practical and special tests using samples or full-scale parts with artificial or natural defects of various sizes. Based on the results of the tests, diagrams of probability of defects detections are built with a confidence probability of 50% and 95% (see figure 1), where the numerical parameters of the probability of defects detection are determined from: defect size which is detected with a probability of 50, 90 and 95% at a confidence level of 50% (a50/50, a90/50, a95/50), as well as defect size which is detected with 90% probability at a confidence level of 95% (a90/95) [5, 6]. The obtained parameters are one of the initial data types for the calculation using the software product "Darwin", designed to calculate the forecast of the lifecycle of a gas turbine engine (GTE) on the basis of a probabilistic approach.

![Diagram of the probability of defect detection (P) dependence on its size (a).](image-url)
Before carrying out experimental work on the probability of defects detecting in the engine MP as part of general and practical tests, it must be checked that the technological documentation complies with the requirements of existing standards and evaluation of testability of components complies with the applied control methods. Then the part must be divided into specific control zones with special requirements for the NDT method for each zone. Diagrams of probability of defect detection for the zones are derived. These zones are determined by the method of expert evaluation, taking into account factors that affect the process of defects detecting.

One of the main methods of non-destructive testing used in the operation and repair of main engine parts, which has a particularly high level of sensitivity, is the fluorescent penetrant inspection (FPI), which detects surface defects with an opening width of 1 µm or less. The main factors for FPI that affect the process of detecting defects are: the roughness and stress-strain state of the surface of the part, its geometry, availability for inspection, ensuring uniform and sufficient application of defectoscopic materials on the surface of the object of control, and applied control technology.

The FPI method, along with many advantages, such as the relative simplicity of the technological process, high performance, visibility when registering results, has a number of disadvantages, among which those that should especially be highlighted are: the inability to apply a uniform layer of thickness corresponding to a given range of defectoscopic material – film developer in hard-to-reach places of parts of complex geometry, as well as the need to ensure direct visibility during inspection and registration of control results.

For FPI control of engine MP, a highly sensitive set of defectoscopic materials LUM1-OV with the 1st sensitivity class according to GOST (State Standart) 18442 is mainly used, which includes the LZh-6A penetrant, the cleaner OZh-1 and the PR-1 diffusion film-forming developer. Defectoscopic materials, such as penetrant and cleaner, can be applied by submerging the part in these liquids, but the developer must be applied in a thin uniform layer with a thickness of 10±5 microns using a paint sprayer at a pressure of 2-4 atm. according to OST (Standart) 90282 [7]. This thickness of the developer ensures the extraction of the optimal amount of penetrant from the cavities of surface defects to form an indicator pattern, forming a sufficient layer of luminofor containing film that provides luminescence under the UV radiation. An increase in the thickness of the developer layer may lead to no detection of small defects, due to insufficient concentration of the fluorescent dye extracted from the surface defect cavity in the formed layer of the developer paint. In turn, reducing the layer’s thickness may lead to insufficient contact for diffusive interaction of the penetrant with the developer in thin layers.

The scope of control of aircraft engine design elements, including FPI, is set in the design documentation, taking into account the degree of responsibility of the part and the conditions of its operation as part of the product. This scope of control is taken into account when drawing up technological documentation regulating the FPI process at the enterprise conducting the control. In most cases, MP of gas turbine engines have many structural elements and a complex configuration, due to the need to achieve the required performance characteristics. Herewith, these zones are usually among the most loaded, and require 100% surface control. However, operating experience shows that, for example, such structural elements of parts as holes, root slots, collars, root slots, etc. in the MP of aircraft engines may be uncontrollable.

Methods for experimental determination of the size of uncontrolled zones are presented neither in domestic nor in foreign literature. Foreign sources show only the conditions under which the results of FPI control deteriorate and the coefficients of the possibility of detecting defects by various methods of control on the internal surfaces of holes with a depth of less than one diameter for unilateral access and two diameters for bilateral access (D1), as well as the possibility of detecting defects on the internal surfaces of holes with a depth exceeding the dimensions of one and two diameters (D2) [8]. These coefficients are shown in table 1.
Table 1. Control methods’ relative ability to detect cracks on the inner surface of holes during manual control.

| Control methods | Etching | Visual | Magnetic Particle Inspection and Liquid penetrant testing | Eddy current |
|----------------|---------|--------|----------------------------------------------------------|--------------|
| D1             | 5       | 5      | 5                                                        | 2            |
| D2             | 3       | 4      | 3                                                        | 2            |

where the ability is: 1 = excellent; 2 = good; 3 = sufficient; 4 = poor; 5 = low or absent.

Domestic literature sources provide information about the possibility of checking the inner surface of the holes and the surface of the root slots at a depth equal to the diameter of the holes and the width of the root slots [9]. Based on operating experience, for example, for aircraft engine disks, it has been found that the holes are not controlled by a luminescent set of LUM1-OV at a depth exceeding one diameter, and the lower part of the teeth is not controlled in the root slot of herringbone type locks. Examples of uncontrolled zones are shown in red in figure 2.

![Figure 2. Uncontrolled zones in the GTE disk with FPI method.](image)

As a rule, the controlled zones are set analytically due to the impossibility of direct application of defectoscopical material (developer PR-1) on the surface of these structural elements of the detail.

The quality of application of the developer PR-1 on the surfaces of controlled details available for direct observation when performing FPI control is determined by samples of whiteness. These samples, as well as sensitivity samples for FPI control [10], may consist of fragments of details having a simple geometric shape, with the thickness of the surface developer layer closer to the maximum allowed (15 microns). Samples with white-coated layer applied by developer PR-1 with the minimum allowable film thickness are not produced.

2. Experimental study

As part of the task of evaluating uncontrolled zones, experimental studies have been conducted. These studies take into account one of the main factors that affects the process of defects detecting - the quality of applying film-forming developer PR-1 to hard-to-reach areas of aircraft engine details when using standard technology. To illustrate the results, a luminescent composition similar to the film-forming developer PR-1 has been selected. This composition has a white color in daylight and a conditional viscosity in the range of 15-20 s. These parameters ensure its similar application on the surface of the studied objects, forming a solid indelible gray-white film. What is different about this coating is that when illuminated in the ultraviolet region of the spectrum, its luminescence occurs on the surfaces of the objects under study. The advantage of the luminescent composition is that under UV irradiation it is easy to discover even a small amount of it on an examined surface.

High-loaded in operation structural elements of disks, such as holes and root slot of herringbone type locks have been selected as study objects. In these zones, there is a high probability of defects such as cracks of low-cycle fatigue during operation, so their examination is of great interest. To study these zones, we have selected samples of blades that imitate root slots of herringbone type locks of
different widths in the GTE disk (see figure 3A) and made dismountable samples with holes of different diameters (see figure 3b) [11].

Figure 3. Samples simulating the root slot (a) and holes in the disk with a depth equal to two diameters (b).

When it comes to the surface of samples of herringbone type locks slots and the inner surface of holes, it is difficult to determine the thickness of the coating using special tools and devices due to the complex geometry. Using the method of mechanical film removal recommended by the technological documentation is also difficult. In this regard, samples of whiteness and brightness of coatings of various thicknesses of 3.0 microns, 5.0 microns, 8.0 microns, 10.5 microns, 13.5 and 15 microns have been produced to assess the coating thickness. The surfaces of the samples under daylight and UV light are shown in figure 4.

Figure 4 shows that the coating’s thickness, the contrast and the brightness of the white color increase while the brightness of the luminescence increases in brightness samples. It has also been noticed that when applying the minimum allowable coating thickness of 5 microns in UV light, the uniformity of application is not ensured. The presence of a coating with a thickness of less than 5 microns on the whiteness samples is difficult to determine, in contrast to the brightness samples, as shown in table 2.

Table 2. Samples of whiteness and luminescence brightness samples required to assess the thickness of the coating applied.

| The thickness of the coating in microns | 3 | 5 | 15,0 |
|----------------------------------------|---|---|------|
| The surface of the sample in visible light | ![Image] | ![Image] | ![Image] |
| The surface of the sample in UV light | ![Image] | ![Image] | ![Image] |
To assess uncontrolled zones, the luminescent composition has been applied directly on the surface of the root slot of herringbone type samples and holes samples using a spray gun at a pressure of 4 atm., providing a layer of thickness close to the maximum allowed (15 microns) in areas with direct access. When applying the composition, the samples were oriented on the turntable table in the same way as the structural elements of the disk, as shown in figure 5. Since during operation the holes in the GTE disk are most likely to have cracks in the circumferential direction, the disassembled samples of holes were oriented with a cut along the radius to the center of the turntable to get a more complete picture of the coating distribution in the circumferential direction.

![Figure 5. Layout of sample holes and root slot on the turntable table during testing.](image)

The results of directionally coating the surface of the studied structural elements under UV and daylight are shown in figure 6.

![Figure 6. Results of coating the surface of the root slot (a) and the hole (b) in UV and daylight.](image)

Figure 6 shows that it is possible to reliably assess the uniformity and sufficiency of the thickness of the layer of the formed coating on the surfaces of structural elements with a comprehensive assessment of the luminescence brightness and whiteness of the formed film in ultraviolet and visible radiation.

The results of applying a luminescent composition to the inner surfaces of samples of different diameters and herringbone type root slots are shown in figures 7 and 8, respectively. They also show the areas of guaranteed uniform coating, highlighted in the figures, by visually comparing the luminescence brightness to the results obtained from a sample with a layer thickness of 5 microns.

![Figure 7. Results of applying the luminescent composition on the inner surfaces of samples with holes of different diameters (a). The surface of the luminescence brightness sample with a coating thickness of 5 microns (b).](image)
3. Results and discussion

According to the results of experimental studies on samples of luminescence brightness, it has been found that at the minimum recommended thickness of the film developer layer - 5 microns according to OST 1 90282, uniformity of its application on the surface of GTE parts may not be achieved.

According to the results of experimental studies on the application of film-forming developer on samples simulating holes in the disks of GTE, it has been established that:

- uniform application of the film-forming developer with a thickness of 5-15 microns (according to OST (Standart) 1 90282), even with a directed method of application, is carried out to a depth much less than the diameter of the hole;
- the area of sufficient and uniform coating on the inner surface of the holes gets bigger with the holes’ diameters increasing;
- application of the developer to the inner surface of the hole is uneven in depth: with a maximum - in the radial direction to the center of the GTE disk and a minimum - in the axial direction, where cracks are most likely to occur during operation;
- the data presented in literature, technical and technological documentation on the controllability of holes differs from the experimental results, as shown in figure 9.

In accordance with the results of experimental studies on the application of film-forming developer on samples simulating herringbone type root slots in the GTE disks, it has been found that:

- application of the developer on the surface of the herringbone type root slots, with a directed method of application, is not even and is insufficient in the center of the root slots in the area of the lower part of the teeth and depressions, where cracks may occur during operation.
- the data presented in literature, technical and technological documentation on the controllability of root slots differs from the experimental results, as shown in figure 10.
Figure 9. Sections of uncontrolled zones in root slots from literature sources (a), technical and technological documentation (b) and experimental studies (c).

Currently, in the aviation industry, there are more and more requirements for the safety and reliability of products [12, 13, 14], so to ensure 100% control of the surface of a complex MP configuration, within the framework of the applied technology, it is necessary to ensure the use of special devices for applying film-forming developer in hard-to-reach places, to apply other capillary control technology, for example, using a powder developer [15] or other NDT methods.

4. Conclusion
The approach is shown to determine uncontrolled zones on the surfaces of holes and root slots of the MP during capillary control.

It is proposed to use luminescence brightness samples as an indicator of the thickness of the developer layer, which allows us to evaluate zones with coating thicknesses of 5-15 microns on the surfaces of structural elements of GTE parts.

It has been established that even with the directed application of the developer, the controllability of holes and herringbone type root slots worsens with a decrease in diameter and width, respectively, allowing to detect only defects that have an exit to the edge.

It has been found that the data presented in literature, technical and technological documentation on the controllability of holes and herringbone type root slots differs from the experimental data.

The proposed approach should be used to determine the uncontrolled zones of all aircraft engine MP when certifying the technology of capillary non-destructive testing, using film-forming developers, according to OST (Standart) 1 01207 in the framework of general and practical tests at various engine-building enterprises of the aviation industry.

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