Acoustic Methods for Testing Gas Turbine Engine Blades

V N Trofimov\(^1\), I N Pyankov\(^{1,2}\) and V A Pyankov\(^2\)

\(^1\)Dynamics and Strength of Machines Department, Perm National Research Polytechnic University, 29, Komsomolsky prospect, Perm, 614990, Russia
\(^2\)United Engine Corporation - Perm Motors, Perm, Russia

E-mail: tvn_perm@mail.ru

Abstract. In this paper the application technology of the ultrasonic testing method in the process of the PS-90A aircraft engine manufacturing is considered. It is known that the development and implementation of monocrystalline turbine blades for aircraft gas turbine engines are aimed at ensuring the material effectiveness or increasing the blade service life in comparison with polycrystalline blades. It is achieved at the cost of the increased long-term material strength in the same temperature range. Based on the results of the process and metallographic studies analysis, it has been established that during the structure formation under the internal stress action, hot crystallization cracks with an opening from 3 to 8 µm or more and a length of 3 to 35 mm along the grain boundaries can appear. Grains formation in most blades happens with their subsequent exit to the lock end, a bridge. The formation of hot cracks most likely occurs at a large grain disorientation angle (more than 25°). Grain boundaries on blades with hot crystallization cracks are located, as a rule, on the bridge at the junction of the blade root with the blade shank (“bottleneck”) with orientation along the blade axis. The method of contact laser-ultrasonic flaw detection (CLUFD) was tested on blades in the region of bridges using both pilot samples and standard parts in order to solve an urgent production and technical problem, that is timely detection of hot crystallization cracks in rotating turbine engine blades at the manufacturing stage. The use of the phased antenna array technology (PAR) in combination with a portable X-32 flaw detector represents a new level of blade ultrasonic testing. The flaw detector operates in a wide frequency range, which allows solving a very large range of various ultrasonic testing problems. The advantages and possibilities of the PAR technology with the portable X-32 flaw detector can be considered on the example of the turbine blade lock testing. S-scan (sector-scan) makes it possible to interpret the received signals quickly and easily.

1. Introduction
It is known that the development and implementation of monocrystalline turbine blades for aircraft gas turbine engines are aimed at ensuring the material effectiveness or increasing the blade service life in comparison with polycrystalline blades. It is achieved at the cost of the increased long-term material strength in the same temperature range.

High-temperature destruction of polycrystalline blades, as is known, occurs in the weakest places, which are grain boundaries. A single crystal blade usually consists of one or several macrograins, whose boundaries are transverse to the external load. And since there are few or no such boundaries in single-crystal blades, this circumstance ensures a significantly longer blade service life.
Vacuum precise casting is widely applied for manufacturing high-pressure turbine rotor blades for the 1st and 2nd stages of the PS-90A engine using the models cast from heat-resistant nickel alloy ZhS32-VI by means of the high-speed directional solidification method.

Blades have a complex structure with cooling channels in the inner cavity, divided by 1.5 mm thick bridge edges. Cooled turbine blades are hollow structures with various air-cooling channels (radial channel, deflector channel, etc.) made of polycrystalline equiaxed, directional and monocrystalline structures by the method of investment casting.

Many studies have established and experimentally confirmed that, according to a set of turbine blade strength properties the [001] direction is an optimal axial orientation. Monocrystalline rotating turbine blades of modern gas turbine engines are cast with such an axial orientation [1].

A blade structurally consists of several macrograins, whose boundaries are located mainly parallel to the blade axis. The growth of one grain relative to another occurs in crystallographic directions. Due to the arising internal stresses, the grain boundary may go unparallel to the crystal growth axis in the [001] direction. This can be indicated by the internal grain growth and the rotation of the grains relative to each other at a certain angle. Hot and cold cracks occur in castings due to the internal stresses that are greater or comparable to the tensile strength of the material. Both grain boundaries and the grains themselves are destroyed in the process of their formation.

Large-angle grain boundaries have a significant negative effect on the parameters of the material strength properties. This fact necessitates the rejection of blades. Particularly stringent requirements for this quality parameter are imposed on blades crystallized from alloys with a low carbon content, where the strength of high-angle boundaries is low.

Research in the crystal structure perfection of a single crystal heat-resistant alloy [2] shows that the volume of a single crystal is divided by several level boundaries into large blocks (with disorientation angles in several degrees). Each block is divided into smaller blocks with disorientation angles in less than 1°, and they, in turn, into even smaller ones.

Based on the results of the process and metallographic studies analysis, it has been established that during the structure formation under the internal stress action, hot crystallization cracks with an opening from 3 to 8 μm or more and a length from 3 to 35 mm along the macrograins boundaries can appear. The formation of grains in most blades occurs with their subsequent exit to the lock end, a bridge. The formation of hot cracks most likely occurs at a large grain disorientation angle (more than 25°). The grain boundaries on blades with hot crystallization cracks are located, as a rule, on the bridge at the junction of the blade root with the shank (“bottleneck”), oriented along the blade axis.

2. Materials and blade defects

Turbine blades (TBs) are the main parts of a gas turbine engine (GTE) which operate at high temperatures and are exposed to high static, vibration and temperature stresses. They are exposed to both corrosive and erosive gases. The strength characteristics of operational TBs determine the engine reliability and its service life. In particular, the breakdown of the operational TB can lead to a non-localized engine destruction. JSC “UEC-Perm Motors” widely uses non-destructive testing methods in the manufacture of the PS-90A gas turbine engines for medium-range and long-range aircraft Tu-204, Il 96-300, etc.

Possible defects (Figure 1) of the turbine blades made by casting methods, in particular by the method of high-speed directional solidification (HSDS), are hot crystallization cracks with an opening from 3.0 to 8.0 μm and more and a length from 3.0 to 35.0 mm along the macrograins boundaries. Hot crystallization cracks appear when the structure is formed under the influence of internal stresses. The formation of grains in most blades occurs with their subsequent exit to the lock end, a bridge.

Cracks are defects of the TB locking part after the gas turbine engine operation. The central and edge regions of the first spline groove of the TB locking part is the area of the most probable
crack initiation. Cracks parallel to the splined groove have a length of 0.5 to 3.0 mm, a depth of 1.0 mm and a width of 0.2 mm.

Figure 1. Bridge of the blade locking part: with the crystallization crack (a); with the macrograin boundary (b); with the slag clogging (c).

3. Advanced methods for non-destructive cast blade testing

At present, in order to prevent the usage of blades with hot cracks in production, serial bridge macrostructure testing in the region of the blade roots and shank is carried out, taking into account additional requirements for grain boundaries with the intersection of specially defined zones and the introduction of a maximum disorientation angle, which should not be more than 25° (The angle was determined by statistical data). Inspection of the turbine rotating blades is performed by two testing methods: visual-optical and X-ray (the Laue method).

The first stage of cast aircraft engine blade inspection is visual-optical (visual). Testing is carried out with the use of lighting and magnifying optical devices that help to see the crystal boundary better and determine the crystal disorientation. Re-inspection of the blades that do not meet the disorientation angle standards is carried out by X-ray diffraction analysis (the Laue method) using the KROS PRDU installation.

The installation includes an X-ray protective camera, a workstation, a system control panel and a Digora Optime laser reader. The software solves the problem of automatic recognition of the Laue reflexes, determination of their coordinates and transformation of the epigram into a stereographic projection. The accuracy of orientation measurements should be determined by parallel surveys of specially selected samples using a diffractometer. The surface of the inspected object must be prepared in advance. The surface of the investigated blades is prepared by etching, just as for the macrostructure testing in accordance with the serial part production technology. If necessary, in order to improve the quality of the epigrams, the inspection site can be etched locally in accordance with the manufacturing technology of the part.

It is allowed to produce blades with a grain disorientation angle of up to 25°. The problem appears when grains are disoriented at 25°–26°. Cast blades with such a disorientation of macrograins are classified as defective. Defective blades are very expensive for production operation. The total number of discarded blades reaches 20–40 %.

However, the measurements made do not always show the actual state of the bridge macrostructure along the entire length of the blade shank and root. The boundaries of two grains on the surface and in the bridge of the part may not coincide. The assessment of a grain boundary transition from one zone into another (on the blade back and pressure side) is inaccurate.

The analysis of the blade defectiveness showed the need to improve the technological process of non-destructive blade testing, taking into account their design features and elastic properties, in particular, cast nickel alloy ZhS32-VI.

The method of contact laser-ultrasonic flaw detection (CLUFD) was tested in the bridge region using both pilot samples and standard parts in order to solve an urgent production and technical problem, that is timely detection of hot crystallization cracks in rotating turbine engine blades at the manufacturing stage [3].

To carry out blade flaw detection, a UDL-2M flaw detector and a specialized transducer PLU-6P-01 were used (Figure 2). The PLU-6P-01 model is a broadband optical-acoustic transducer,
whose installation in the rotating blade root pocket of the second stage turbine engine for bridge testing is shown in Figure 2c. This method is based on the use of the thermoelastic effect [4].

Elastic waves (longitudinal waves from 0.1 to 100 MHz) are excited in the blade when a sufficiently intense light beam of pulsed laser radiation is exposed to its surface. The laser radiation absorbed by the metal heats the thin surface layer of the blade. The specific radiation power does not exceed the threshold value at which ablation (evaporation of the metal surface layer) occurs. The amplitude of the generated pulses increases when, for example, the metal surface is coated with a thin layer of water or oil, which prevents the expansion of the heating zone. The latter is associated with a change in the longitudinal waves diagram. Their maximum coincides with the normal to the blade surface.

![Figure 2](image_url)

**Figure 2.** The exterior view of the UDL-2M flaw detector (a), the exterior view of specialized sensor PLU-12U-02 (b) and installation of specialized converter PLU-12U-02 on the blade surface (c).

Laser emits light pulses at a duration of 10 nanoseconds with a pulse energy of 0.1 J with a repetition rate of up to 1 kHz. A short laser pulse is transmitted through an optical fiber to an optical-acoustic generator. The subsequent thermal expansion causes the ultrasonic pulses excitation. An excited short broadband ultrasonic pulse propagates deep into the blade under study.

The pulse scatters along the blade structure inhomogeneity. Further, a broadband piezoelectric contact receiver with the PVDF film as a piezoelectric element registers reflected and backscattered longitudinal ultrasonic waves. Reflected and scattered waves carry information about the acoustic properties of the blade metal structure and defects. To obtain a two-dimensional image, the PLU-12U-02 sensor is manually moved along the blade face perpendicular to the bridge under study.

The signals from the transducer are subjected to time and frequency filtering with subsequent formation in the matrix.

The final result of the signal processing is the bridge cross-section image on B scan.

A small diameter of the probe pulse increases the sensitivity to defects detection, whose size is equal to or less than the ultrasound wavelength. What is more, with a short ultrasonic pulse duration, high accuracy of ultrasound velocity measurement equal to 1% is achieved. It becomes possible to measure the cross-section of ultrasonic waves back-scattering with a high spatial resolution of up to 0.05 mm, as well as measure the attenuation of ultrasonic waves in a wide frequency range of 0.1–100 MHz. In fact, there is no uncontrolled (“dead”) zone with one-sided access to the part.

Testing is carried out in two main directions with the introduction of longitudinal L-waves: perpendicular to the shank platform and the blade root.

We tested model samples with artificial defects in the form of a 1.5–2.0 mm long and 1.5 mm wide groove, equal to the bridge width. The defects were grooved by the electroerosion method in different bridge regions from the side of the leading (entering) and exit edges of the blades (Figure 3). Bridge testing was carried out in two places: on the shank closer to the root and in the
root pocket. The results of model samples testing are presented in Figure 3. The revealed defects are marked with a circle.

![Figure 3](image)

Figure 3. Results of revealed artificial defects in model samples.

10 castings of the second stage HPTBs were tested by the method of contact laser-ultrasonic flaw detection. Those blades were rejected according to the results of X-ray diffraction analysis done with the KROS PRDU device to determine grain disorientation on the shank. The grain disorientation angle on different blades ranged from 29.5° to 55.9°. Testing was carried out from the tapered part of the shank. Six blades were found relatively acceptable. Four blades were selected according to the availability of ultrasonic waves reflection from the bridge region. After that the samples cut along the bridges were tested by the LUM1-OV1 method followed by the metallography.

Metallographic studies in the course of layer-by-layer metal removal in the bridge cross-section in places with fixed coordinates of the reflected signals showed the presence of grain boundaries. It was found that ultrasound reflection on three out of four blades was due to a pronounced boundary between two adjacent grains. A hot crystallization crack with a length of about 2.0 mm and a maximum opening of up to 0.8 mm was found on one blade from the side of the exit bridge. Metal discontinuity flaw was found in the same blade, in the bridge from the side of the leading (entering) edge.

Taking into account the requirements of serial testing, namely: the introduction of the maximum permissible angle of grain disorientation equal to 25°, as well as having the coefficient value of the ultrasonic wave reflection from the interface, it is possible to introduce the cutoff level of the signal amplitude scattered back from the controlled bridge volume. This will allow increasing the blade testing efficiency by the laser-ultrasonic method. The possibility of using the CLUFD method for the timely detection of hot crystallization cracks in rotating turbine blades is shown experimentally (on the example of model samples and standard blades).

Due to the complex geometry of the blade airfoil and locking piece, it is rather difficult to carry out ultrasonic testing of the blade locking piece using traditional ultrasonic testing methods. The blade geometry limits access to the testing regions. The use of phased array technology (Figure 4) in combination with the portable X32 flaw detector represents a new level of ultrasonic blade testing [5–9]. The flaw detector operates in a wide frequency range, which allows solving a very large range of various ultrasonic testing problems [10–21]. The advantage and capabilities of the PA technology together with the portable X-32 flaw detector can be considered on the example of the TB locking piece testing. When using the X-32 flaw detector and a PAR-transducer, it becomes possible to detect defects in the blade locking piece accurately and determine their location and dimensions. The area of the platform from which the sounding of the blade locking piece was carried out was (10x5) mm².
S-scan (sector-scan) makes it possible to interpret the received signals quickly and easily.
To confirm the validity of the inspection results, an image obtained on the S-scan of the turbine blade locking piece with detected 0.5 mm and 1.5 mm cracks is superimposed on the TB photograph.

Figure 4. Schematic drawings show the probe on the turbine blade and the component layout. All dimensions are given in mm.

The optimal angles of ultrasonic vibrations input are within the sector from 0° to 55°. Signals become less clear at angles greater than 45°.

The inspection results show that an X-32 flaw detector and PAR-transducers allow testing turbine blades more efficiently in comparison with traditional technologies based on the use of a single-channel ultrasonic flaw detector [22].

4. Conclusion
1. Methodologies and techniques for ultrasonic testing of various-sized blades with different purposes for the PS-90A engine and its family were developed and introduced into production.
2. The CLUFD method together with the existing X-ray control method was carried out experimentally using standard and model blades, which made possible to increase the diagnostic informativity of the results when assessing cast blades quality.
3. Testing of the turbine blade locking piece by the PAR technology was carried out experimentally using standard and model blades.

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