

Development of Simple and High-Performance Technology for Compressors

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To reduce the direct operating costs of environmentally compatible engines for small aircraft, highly loaded aerodynamic design technology was developed for the compressor, which could reduce the number of stages considerably while maintaining performance. Three dimensional aerodynamic design was employed using Computational Fluid Dynamics, and the target pressure ratio was obtained from performance rig tests. Diffuser Passage Compressor technology was introduced to suppress tip clearance leakage flows and expand the operating range of small compressors. Effectiveness was demonstrated by low-speed model tests. Linear friction welding and Micro Spark Coating technologies were developed to realize low cost and simple production of the compressor blisks, a term for integrated bladed disks.

1. Introduction

A drastic reduction in direct operating costs comprising acquisition costs, maintenance costs, and fuel costs is pursued for the environmentally compatible engine for small aircraft (ECO engine). To this end, a simple and high-performance design technology is sought in order to maintain high efficiency and to realize a substantial reduction in weight and cost by lowering the number of stages for high-pressure compressors comprising the rotor and stator parts of multiple stages. Furthermore, it is necessary to take the effects of various scales (for example, relative increase in surface roughness and manufacturing tolerance) into consideration to make the engine smaller. In the rear stage where the blade height is lower, the aerodynamic design technology to restrain the effect of the tip clearance flow caused by an increase in tip clearance is vital for ensuring the range of engine operation. Also in terms of structure, production, and maintenance, cutting-edge production technology is required to realize light weight and low cost.

This document outlines simple, high-performance technologies for the compressor developed in the ECO engine project in order to meet these requirements.

2. Target specifications and structure of the compressor

As a result of the preliminary study on the engine cycle, it has been found necessary for its compressor to achieve a pressure ratio of 12 or more with six stages in order to realize the targeted reduction in direct operating costs. Accordingly, the target specifications have turned out to be an increase in loading which halves the stage number, 10 to 12 in state of the art production engines around the world. In order to increase aerodynamic loading while maintaining the performance level, highly loaded blade design technology using CFD (Computational Fluid Dynamics) is required. A multistage compressor was designed and the performance was tested in order to substantiate this technology. (Hereinafter, this compressor is called the baseline compressor.)

The Diffuser Passage Compressor concept, which compresses the air inside the blade row, not by the conventional way of turning the relative flow, but a deceleration of axial velocity as shown in **Fig. 1**, was devised as an aerodynamic design technology to restrain tip clearance flow caused by a relative increase in tip clearance as mentioned above.⁽¹⁾ This concept was intended for suppressing tip clearance flow streaming

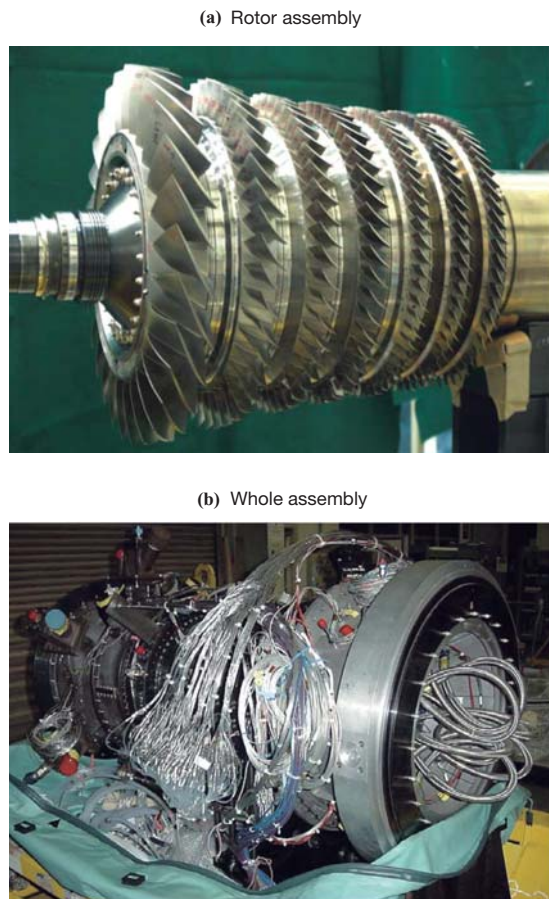


Fig. 3 External view of base-type highly-loaded multistage compressor

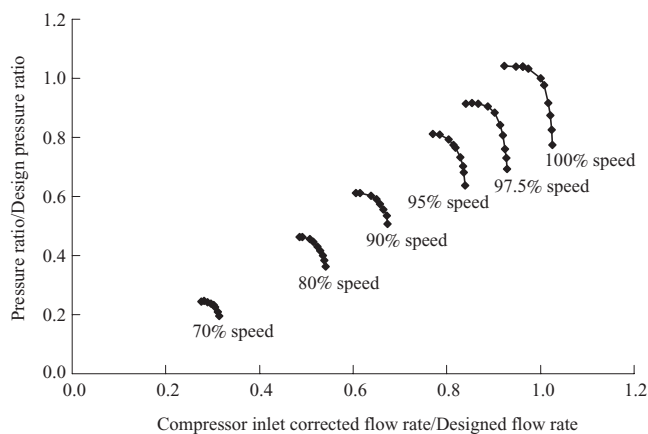


Fig. 4 Test results on overall performance of base-type highly-loaded multistage compressor

temperatures, and so forth are furnished to obtain detailed inter-stage data. **Figure 4** shows the results of the overall performance test. The high pressure ratio, as designed, is achieved at the design speed. Simple and high performance design technology is demonstrated that enables the reduction of the number of stages.

3.2 Study on the performance improvement method for the baseline compressor

The design for improvement is carried out via extraction of improvement areas based on the analysis of the baseline compressor test results, and CFD analyses⁽²⁾ of higher order models including the clearance of a variable stator vane, an inter-stage bleed hole, a fillet at blade root, and so forth. **Figure 5** demonstrates a typical example. A pressure loss reduction is projected for the variable stator vane by optimizing its airfoil shape considering leakage of flow in the clearance at the hub and tip (**Fig. 5 - (a)**). It is also projected that the blade surface peak Mach number of the front stage rotor can be lessened by reviewing the flow pattern (axial loading distribution) and optimizing its airfoil shape (**Fig. 5 - (b)**).

3.3 Substantiation for the performance of the diffuser passage compressor

First, the basic capability of increasing pressure was verified in a wind tunnel test using a Diffuser Passage (DP) linear cascade.⁽¹⁾ Next, a rotating cascade test rig was manufactured in order to compare the DP Compressor and conventional rotor blade (hereinafter called the CNV) in terms of performance in a rotating environment. The test rig has a 1.5 stage configuration (swirl generating guide vane + rotor blade + stator vane) where the rear stage of a highly loaded multi-stage compressor was simulated. Both rotor blades were designed with the same aerodynamic loading level. High to low speed conversion was performed in the design with aerodynamic similarities being maintained so that detailed measurements could be conducted on a larger scale. **Figure 6** demonstrates cross sections of the low-speed model compressor (- **(a)**), (- **(b)**) and the external view of the DP Compressor assembly (- **(c)**).

Figure 7 demonstrates a comparison between the results of overall performance obtained through the radial traverse of yawmeters at each rotor inlet and exit. In **Fig. 7**, the x-axis indicates mean axial velocity at rotor inlet divided by rotor inlet tip speed, whereas the y-axis, a rise in static pressure against the total pressure at rotor inlet divided by the product of rotor inlet density and rotor inlet tip speed squared. Although a stall of the whole compressor occurred at a flow rate slightly lower than the plot at the lowest flow side in each case, stall operating lines for both rotors were drawn in **Fig. 7** according to the definition of the stalling point of a single rotor being specifically located at a peak of a static pressure rise.

As for the CNV rotor blade, the stall flow rate substantially increases as the tip clearance is expanded to approximately double (stall margin decreases); the DP Compressor can be regarded as technology to restrain the occurrence of stalls that come with downsizing the engines in that the stall occurrence flow rate only slightly increases. Furthermore, the pumping

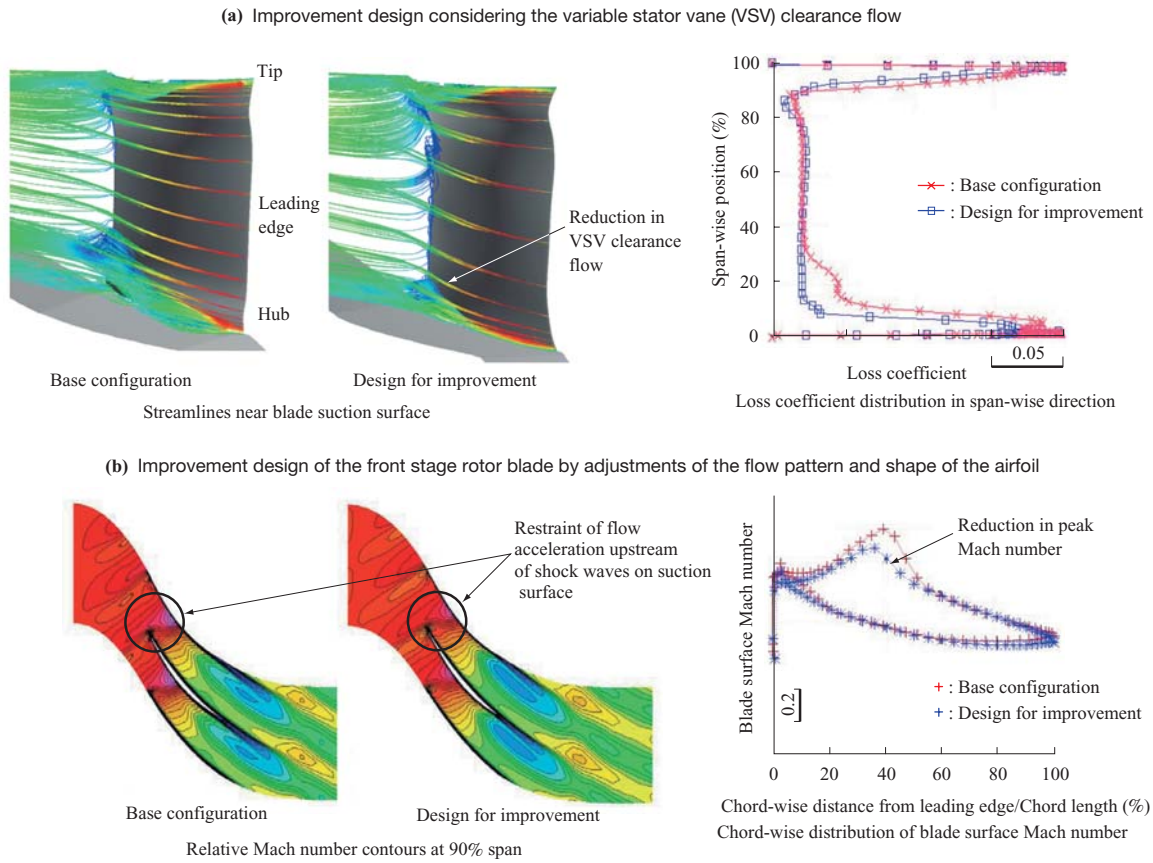


Fig. 5 Redesign of highly-loaded compressor based on base-type test results and CFD with more realistic geometry

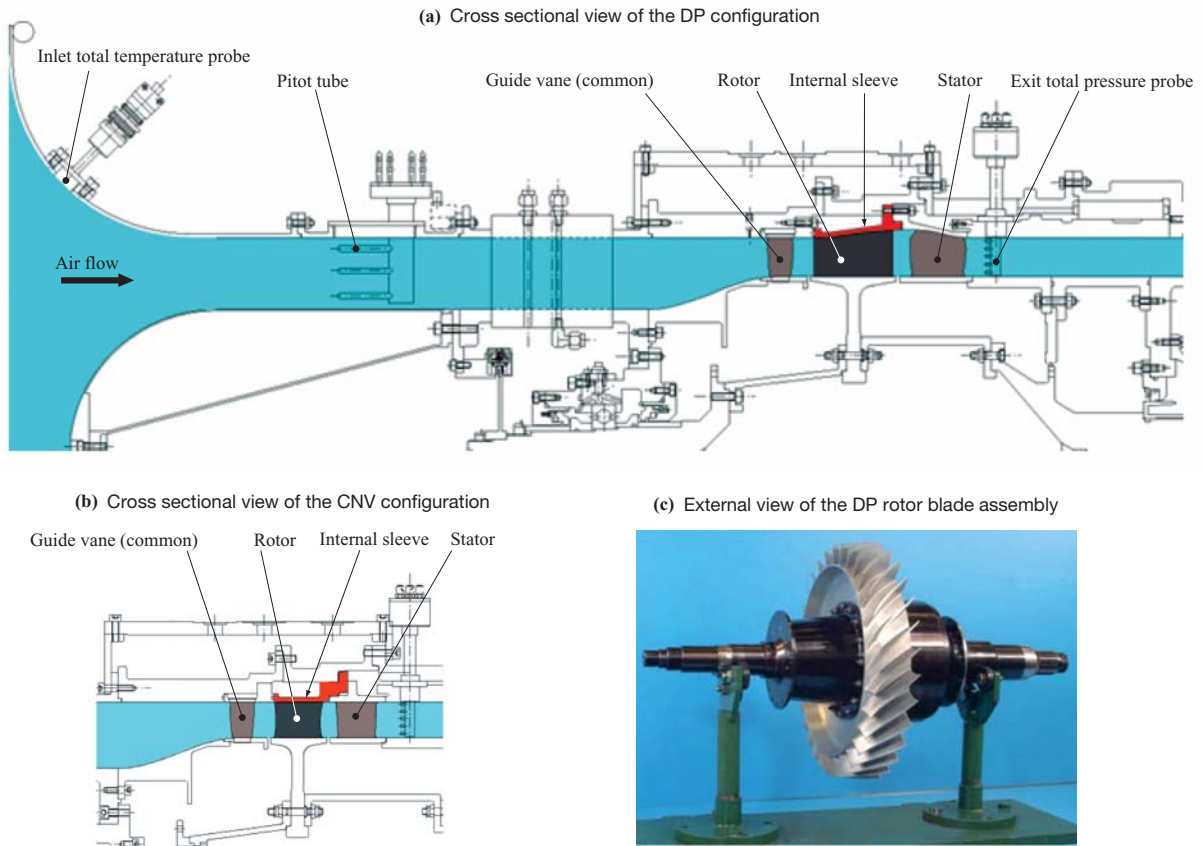


Fig. 6 Cross sectional and external views of low-speed model compressors

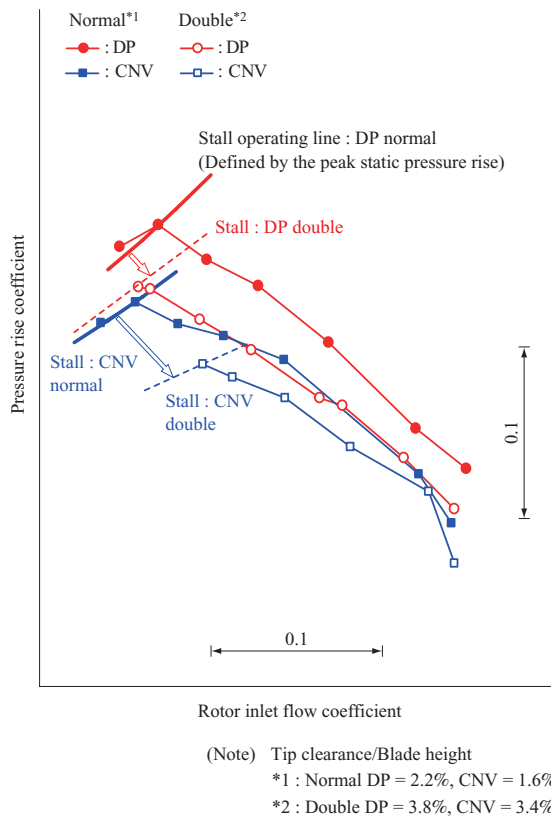


Fig. 7 Comparison of tested performance of DP rotor and CNV rotor

curve of the DP Compressor (flow rate-pressure rise curve) indicates a larger rise in pressure (steeper) versus the drop in flow rate than that of the CNV rotor blade.

As far as the last stage rotor blade of the multi-stage compressor is concerned, the steeper the pumping curve gets, the smaller the change in flow rate at the compressor inlet becomes when the operating line of the compressor as a whole is throttled. Therefore, this is preferable since the front stage side does not need to be throttled. From this perspective, it is thought that the aerodynamic performance of the highly loaded multi-stage compressor can be rendered more robust (a state in which there is less decline in stall margin relative to an increase in tip clearance) by adopting the DP Compressor.

4. Compressor-manufacturing technology

4.1 The development of low cost blisk manufacturing technology

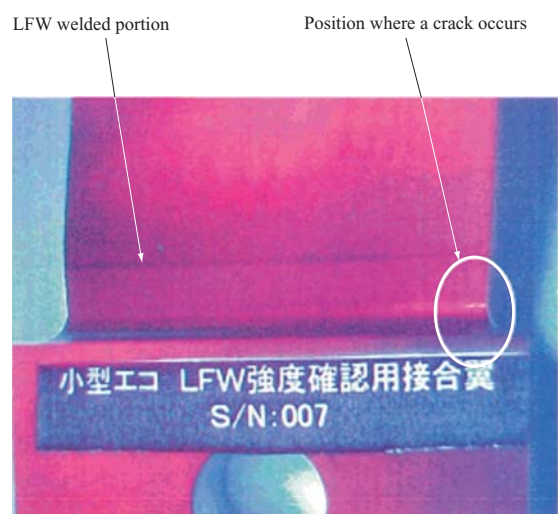
Since the blisk structure has been actively brought up for review due to the demand for high-performance, the development of corresponding manufacturing technology is an urgent necessity. The blisk blade surface is normally processed by carving, causing great loss in material during the rough processing, leading to an abundance of problems concerning production costs. In order to work this out, blisk manufacturing technology was developed by applying Linear Friction

Welding (hereinafter called LFW).

The LFW method is a technology that was developed at TWI Ltd., UK in 1981 - a friction welding method that is not limited to a circular bonding section etc. It is possible to cut down on materials and processing costs thanks to the manufacturing process of welding a blade to a disk. Yet the method has the problem of how to ensure the strength of bonding equipment that can deal with blisk blades and how to head off interference while manufacturing. In this research, after the fatigue test on a blade sample manufactured using the LFW method with the actual geometry, a real-size blisk test rig was manufactured.

Figure 8 shows the test piece (material: Ti-6Al-4V) which was manufactured based on the optimal welding conditions and was provided for the fatigue test. A welding position was determined by analyzing the blade stress distribution prior to the test so that the LFW bonding section could be loaded with ample stress for the manufacture of a simulated blade. As a result of the fatigue test, where no bonding and heat-affected portions were broken, it was verified that the LFW bonding in real blade geometry excelled in endurance.

Figure 9 demonstrates the external view of a real-size demonstration blisk manufactured using the LFW method. There was a concern that the flange provided on a blade as a grip prior to welding would interfere with the blades on both sides of that blade. By devising the jig, however, the manufacturing was successful without any problems even when dealing with the distances between blades expected to be encountered in manufacturing for actual use. Since the LFW method excels tremendously in the degree of freedom in manufacturing, it is possible to apply it to many aircraft engine parts.



(Note) Material : Ti-6Al-4V

Fig. 8 Appearance of blade shape sample after high cycle fatigue test



Fig. 9 Demonstrator blisk manufactured by LFW

4.2 Development of the abrasive coating

The abrasive coating on the blade tip of a compressor was developed using the Micro Spark Coating method (MSCoating: hereinafter called the MSC). The MSC method is our country's original technology used to coat a product surface with elements of a coating block (C/B) made of temporarily sintered metal or ceramic, by means of energy generated by pulse discharge between C/B and the product surface. Various functional coats can be put on by selecting different C/B elements. **Figure 10** demonstrates the principle of deposition by MSCoating.

In an ECO engine, the tip of the compressor blades are made abrasive by coating Titanium Carbide (hereinafter called TiC) via the MSC method. The abrasive coating would restrain wear and tear on the blades during engine operation, resulting in a reduction in maintenance cost. In this research, abrasiveness of the TiC coating, as well as the impact of a hard TiC coating on the high cycle fatigue (HCF) life of the blades are investigated.

The abrasiveness was examined by rubbing a test piece coated with TiC, simulating a rotating blade, with a test piece simulating a stationary casing. The test was conducted assuming two cases, in one the TiC was attached to the lateral, or concave side of a blade and in the other, to the tip of a blade. The test temperature was room temperature; the rubbing speed, 32 m/s; and

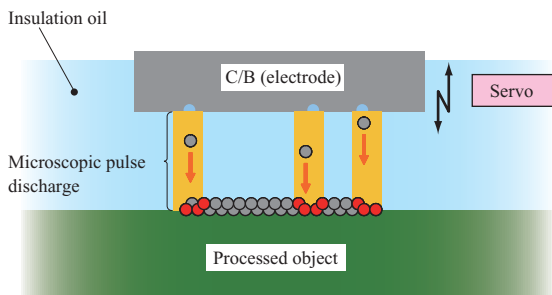


Fig. 10 Principle of deposition by MSCoating

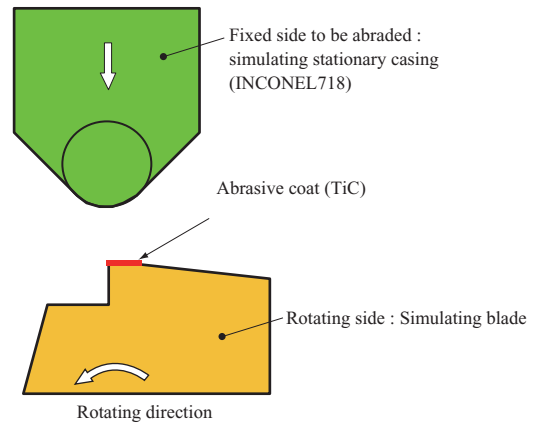
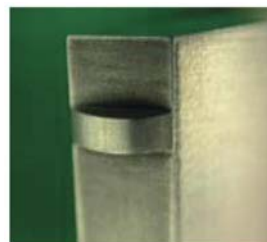


Fig. 11 Test configuration for quality evaluation against abrasion

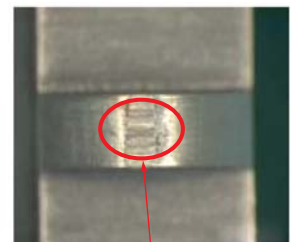
the cut depth, 0.02 mm. **Figure 11** demonstrates the test configuration for quality evaluation against abrasion, and **Fig. 12**, the appearance of the fixed test pieces after the abrasion test. It was confirmed that the desired abrasiveness existed without wear and tear on the TiC.

Next, the HCF life was ascertained (vibration mode in the direction of blade chord at its tip) by attaching TiC to the tip of a real blade and to the concave side nearby. The strength decreased by approximately 13% to 19% compared to the case where TiC was not attached, and a crack appeared on the concave side near the tip of a blade. **Figure 13** demonstrates the appearance of the compressor blade after the HCF test. It is thought that the stiffness of TiC is attributed to the decline in flexibility. It is understood that it is necessary to take this decline into consideration at the time of designing a real product.

(a) Appearance and shape of fixed test pieces before abrasion test



(b) Appearance and shape of fixed test pieces after abrasion test



Shape of portion abraded by TiC coating on the rotating side

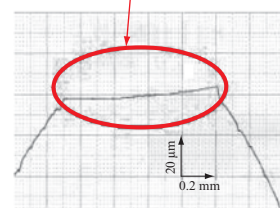
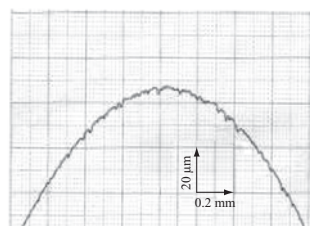


Fig. 12 Appearance of fixed test pieces after abrasion test

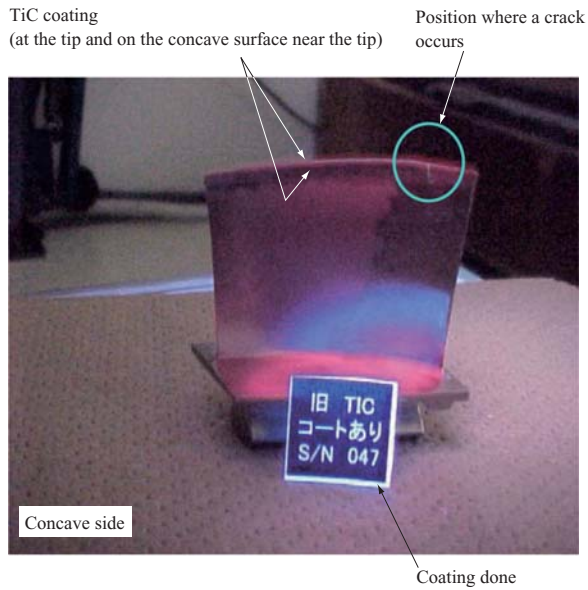


Fig. 13 Appearance of compressor blade after high cycle fatigue test

5. Conclusion

This document outlines the simple and high-performance technology for compressors developed in the ECO engine project.

From the aerodynamic standpoint, a combination of the highly loaded multi-stage compressor developed in this research and the Diffuser Passage rotor blade can be applied to small-size ECO engines, predictably helping to realize the high-performance axial flow compressor with the number of stages reduced more drastically than ever before.

From the standpoint of manufacturing, the LFW technology was able to be adapted to our needs in order to bring down the costs in manufacturing the blisk structure intended for high-performance and lighter weight. It was predicted that the abrasive coating technology MSC would contribute to a reduction in

maintenance costs; issues were brought into focus as well.

It is thought that these cutting-edge technologies will make a tremendous contribution to reducing direct operating costs for small-size ECO engines.

— Acknowledgments —

The present research was carried out with financial aid from New Energy and Industrial Technology Development Organization (NEDO) as part of the “Research and Development of Environmentally Compatible Engine for Small Aircraft” in the civil aircraft basic technology program of Ministry of Economy, Trade, and Industry. The authors would like to acknowledge NEDO and all the other related parties for their support.

In addition, the authors would like to thank Professor Eisuke Ota of Waseda University for his technological support in carrying out the low-speed model compressor tests. The authors would also like to acknowledge Technical Advisor, Dr. Hidekazu Kodama, and all the other related people in Research & Engineering Division and Manufacturing Division of Aero-Engine & Space Operations, and in Production Engineering Center of Corporate Research & Development for their support and contribution.

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