ISSN 0389-4010
UDC 620. 171. 5:
621. 523-226. 5

TECHNICAL REPORT OF NATIONAL AEROSPACE LABORATORY

TR-427T

New Molding Method of Three-Dimensional Hollow Photoelastic Model and Centrifugal Stress Analysis of Air Cooled Turbine Blade Model

Toyoaki YOSHIDA, Katsutoshi MATSUSUE, Kitao TAKAHARA
and Ryosaku HASHIMOTO

May 1981

NATIONAL AEROSPACE LABORATORY

CHŌFU, TOKYO, JAPAN

New Molding Method of Three-Dimensional Hollow Photoelastic Model and Centrifugal Stress Analysis of Air Cooled Turbine Blade Model*

Toyoaki YOSHIDA, Katsutoshi MATSUSUE,
Kitao TAKAHARA and Ryosaku HASHIMOTO**

ABSTRACT

A new molding method for a three-dimensional hollow photoelastic model was invented and centrifugal stress analysis has been performed for air cooled turbine blade models to which the new method was applied.

A distinctive feature of the molding method is the introduction of a copper coated wax core which forms a three-dimensional hollow shape inside a model. The air cooled turbine photoelastic model with a coolant passage simulates the first stage rotor blade in the high temperature turbine full scale model HT-10H used at the NAL. The results of stress analysis cleared the critical regions and stress magnitude and thus they are of great aid to the successful development of a full scale turbine model.

概　　要

中空部のある三次元物体の光弾性模型を製作する新しい方法を考案し，冷却タービン動翼模型に適用して，遠心応力の解析を行った。製作法の特長は複雑な中空形状を成形するための中子の製作と離型にある。すなわち中子は，基材としてワックスを用い，シリコンゴムの型により中子形状を成形した後，表面に銅の薄膜を電着させて作られる。光弾性模型用樹脂を鋳込んだ後の中子の離型は，熱風によりワックスを融解除去し，残った銅皮膜を化学的腐蝕により排出する。この方法は寸法が小さい模型にも適用でき，従来解析の困難であった構造物の応力分布を知ることができる。

航技研で開発研究を行っているターボファンエンジンFJR710のタービン動静翼は空冷化されており，冷却空気通路を設けたために肉厚の薄い部分ができている。特に動翼は高い遠心力場にあるので中空形状の設計・評価には三次元的な応力解析が非常に有用である。このため上記光弾性模型の新しい製作法を適用して冷却タービン動翼模型を作り，応力凍結法を用いて遠心応力の三次元解析を行った。実験の結果，応力の集中する部分とその大きさが明らかとなり，中実翼の場合に比べて重大な欠点となるような値は現出していないことがわかった。

INTRODUCTION

As an effective method for stress analysis of a three-dimensional complicated hollow body, a photoelastic test has been widely introduced and making progress with various inventions and improvements in manufacturing technique of a model. There exists a wide variety of technique in accordance with a size and a shape of a subject to be analyzed. Among those, it is considered very effective to adopt silicone rubber as mold material. Such attemptions have been presented

* Received 18 March 1981
** Aeroengine Division

elsewhere 1), 2) and their validity is well accomplished.

While it might safely be said that stress analyses of air cooled turbine blades have been insufficient due to the complexity of coolant passage shapes formed inside the blades, although they are required as closely and accurately as possible. Thus the present study has been performed as an aspiring one of our researches 3).

As to a molding method, simplified hollow models such as a cylinder and various candidate material for a core were chosen and casting conditions were surveyed in the early stage of the study. Consequently the introduction of a copper wax core showed the best aspect to meet our purpose. This, a kind of invention, was achieved in collaboration with the Photo Cutting Laboratory Co., Ltd.

Centrifugal stress analysis with a photoelastic model of hollow turbine blade was performed by the frozen stress method. Detailed description on the molding method and the experimental results are given in this report.

MOLDING METHOD

At first, any material can be used as a pattern as far as it remains unchanged in its structure inside a container during the period when liquid silicone rubber is poured and grows hard at room temperature. In the present case, an actual air cooled turbine blade made of superalloy and a core made of ceramic are applied as the patterns.

Molding procedure with the use of silicone rubber is already described in Reference (1). A gating system, open risers and clamping method were not satisfying until several trials had been made because an every pattern needs its own appropriate casting conditions in general. Two piece mold type was adopted here but it is not a cope and drag one, see Fig. 2.

Fig. 1 shows a procedure of the present molding method and some photographs are shown in Fig. 2 in which notations corresponding to the procedure are marked. Three kind of patterns were chosen as test models, one is a solid blade and the others are hollow blades. All the

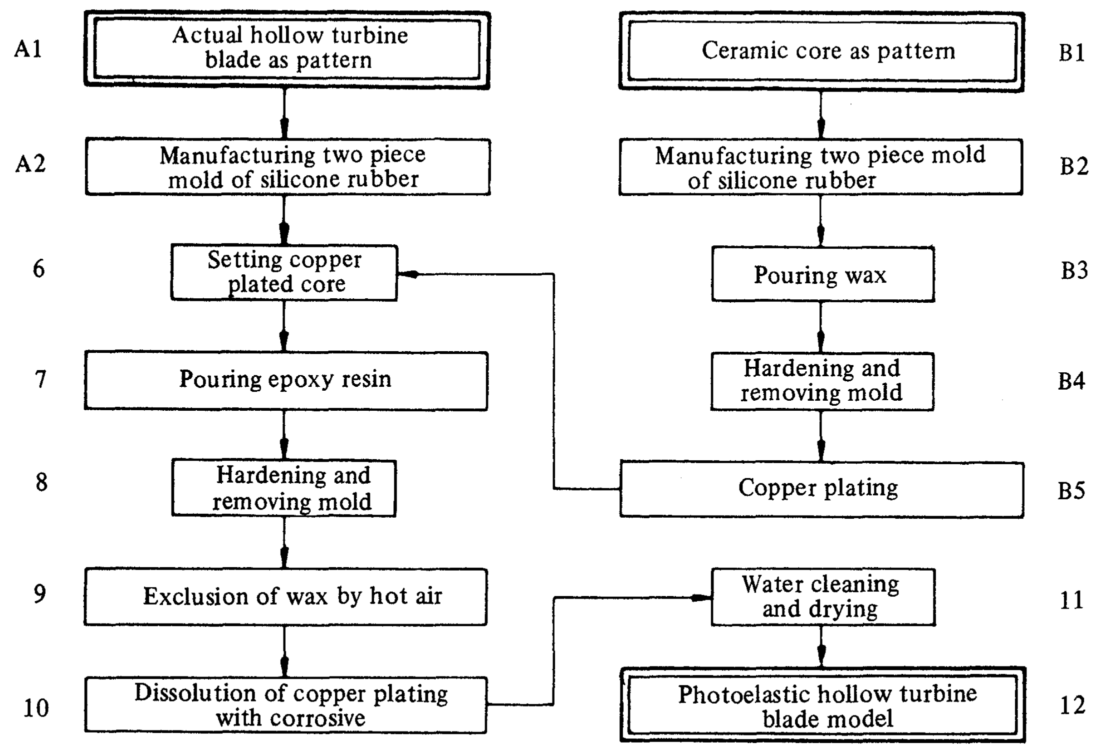


Fig. 1 Manufacturing procedure of three-dimensional hollow photoelastic models

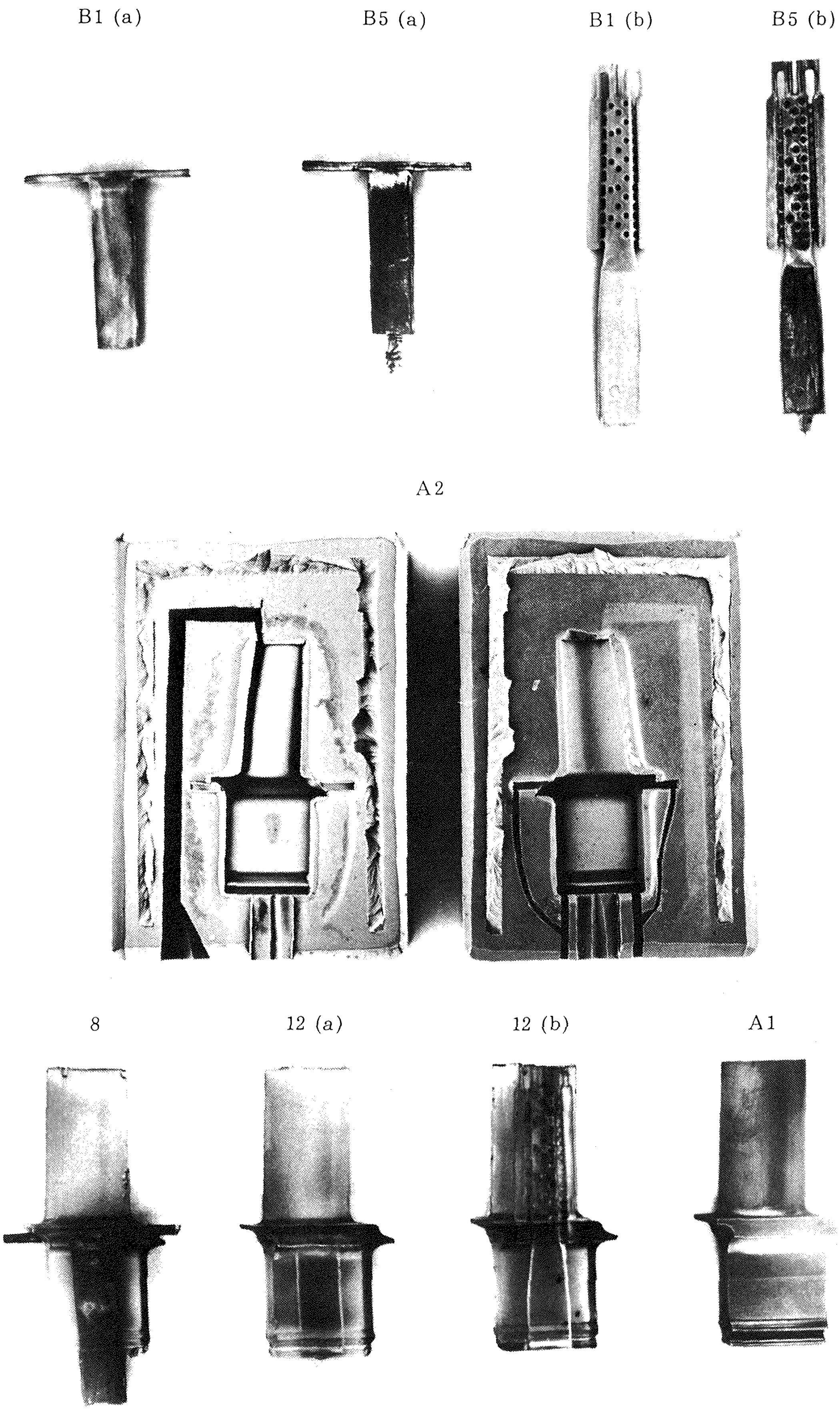


Fig. 2 Photographs at some manufacturing steps
(Notation coincides with it in Fig. 1)

blades have the same outer shape, see hollow blades 12 (a) and (b) in Fig. 2. A kind of epoxy resin, Alardite B + Hardening (HT-901) is used as photoelastic material. When a core has complicated shape, it can be neither a type of an assembly, nor a type destroyed after hardening of a model material. Thus it should be removed by some kind of liquefied method. In the case of an actual hollow blade made of superalloy, a ceramic core is extruded with a hot alkali solvent. However this method of removal is seriously harmful to the epoxy resin in the present case. As a liquefied method, low melting point alloy so called wood metal was firstly adopted and tried but it was difficult to maintain a shape of core itself due to relatively high temperature while pouring molten epoxy resin, and exclusion could not be successful, neither. A preliminary check to use some water soluble nonorganic matter was then performed whether it could be core material or not. This was consequently too soft to form and maintain a shape of core. Finally the method shown in Figs. 1 and 2 was successful.

Most important features are to use wax of which melting point locates about 60°C and is enough lower than any transition temperature of epoxy resin, and then to apply copper plating onto a wax core with an order of 20 micron in thickness. This order of thickness guarantees a rigidity to maintain a shape of the core and even not to deviate seriously from a designed dimension of the core. Wax is excluded by hot air at a part of the core protruding from the hardened epoxy model where copper plating is scratched in advance, see the bottom part of photographs B5 (a) and (b) in Fig. 2. Copper plating left in the epoxy model is dissolved with corrosive $FeCl_3$. While molten epoxy resin is poured, process 7 in Fig. 1, wax core swells due to high temperature of the resin and that results in deformation of a shape of coolant passage.

A typical result is shown in Fig. 3, where an expansion of coolant passage in up-and-down direction in the figure and a shrinkage in outer shape are observed. This cross section is of an extended root in the blade model. This kind of expansion would be suppressed if copper plating is more thickened than in the present case and scratching a part of it is done before pouring molten resin. In that case, however, the dimension of a core pattern should be diminished in size, taking the thickness of copper coating into account. If more appropriate core material could exist, it should have at least the following fea-

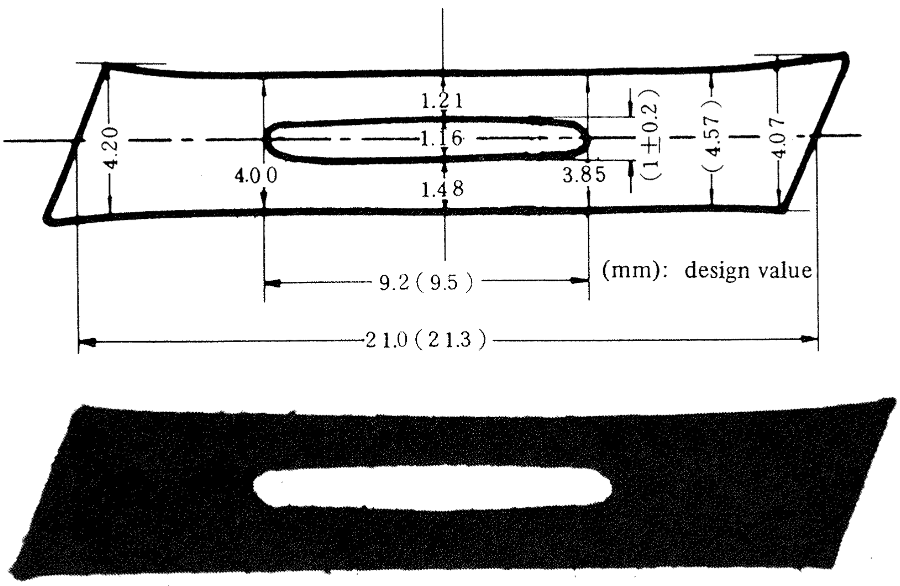


Fig. 3 A typical dimension of epoxy model

tures. That is to have a small thermal expansion rate and to be soluble with some fluid such as air and water at relatively low temperature and most importantly to maintain a designed shape until an exclusion process is done.

A photoelastic epoxy model that can be manufactured, depends on the possibility whether silicone rubber mold is obtainable or not both for the outer shape of the model and the core. Furthermore uniform copper plating on the whole surface of the core material is strongly required. In this sense, the model (b) shown in Fig. 2 could not be satisfying because of the existence of many small rugged passages. A local deep and small dent is particularly difficult to be coated thinly with copper. In the present case, a group of dents of 1 mm in diameter and 1.3 mm in depth seen in the mid region of the blade model (b) could be covered with a copper plating satisfactorily. This dimension of a dent would be a limit of satisfactory copper plating. As easily suggested from the description of the above molding method, a wide variety of applications of small and even complicated hollow photoelastic models can be expected.

CENTRIFUGAL STRESS ANALYSIS

Description of Epoxy Model and Actual Turbine Blade

The purposes of centrifugal stress analysis of turbine blade epoxy models exist in getting an information of critical location and its stress magnitude in view of mechanical strength, and considering the fitness of a coolant passage formation. Analyses performed in the present study involve photoelastic tests of a solid blade model and hollow blade [model (a) in Fig. 2], various considerations such as correction of data to the actual turbine blade, and comparison between the present results and the earlier work 4) in which two-dimensional photoelastic test has been

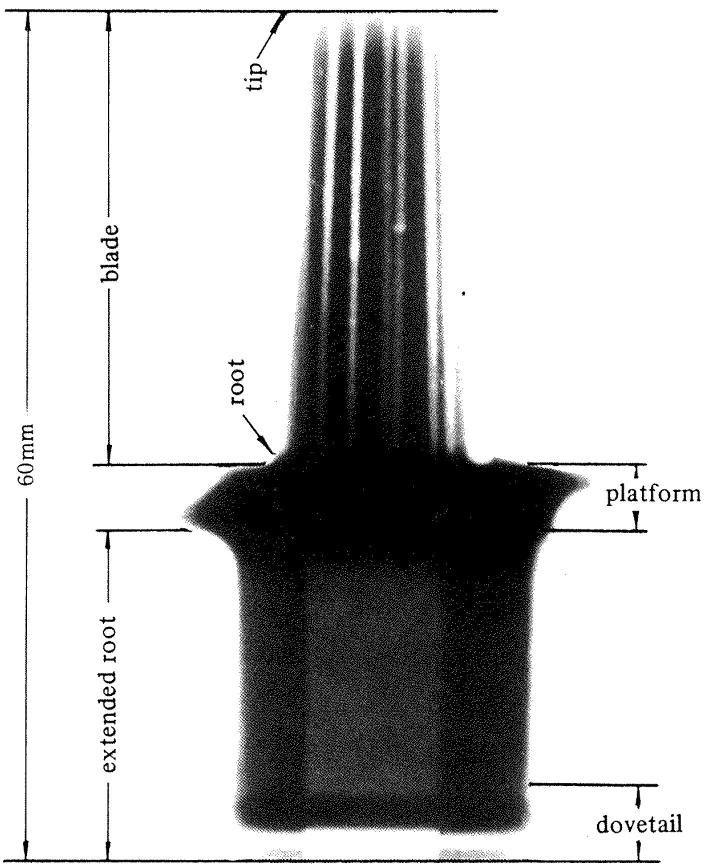


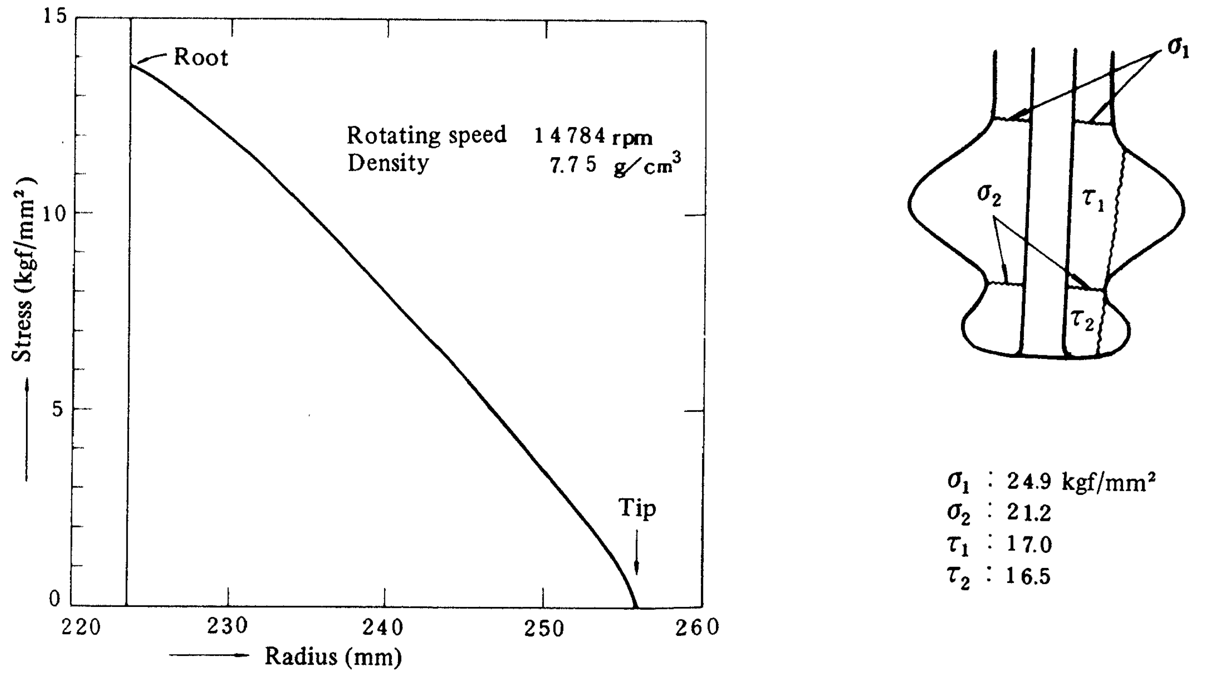
Fig. 4 X-ray photograph of actual turbine blade

done under the condition of tension to the model with a similar shape to a selected section of the present hollow model. Centrifugal stress analysis by photoelastic test, is basically owing to the frozen stress method, thus a model is cut into thin slices which should contain a section expected very important. In this sense, model (b) in Fig. 2 is hardly applied to the test because of the difficulty in getting a thin slice without any damage.

Fig. 4 indicates an X-ray photograph of the actual hollow turbine blade model under the development. It has some ten small cooling holes with diameters of 0.5-1.0 mm in the spanwise direction at the blade section. They are connected to a T shaped coolant passage located inside the platform and the extended root. In the photoelastic model, these small holes are not formed because of the difficulty in manufacturing technique and the little influences on the stress distributions around the coolant chamber in the platform and the dovetail region in which some critical regions would be expected to appear. The contribution of these small holes to the whole blade is of 4% in weight.

The actual turbine blade suffers bending force through fluid flow, thus it is set to the turbine disc with an appropriate offset angle so that the bending force may be eliminated with the designed centrifugal force exerted. In the present photoelastic test, model blades are confined to a container which rotates together with the models, therefore the blade models hardly receive fluid pressure. A difficulty in similarity between the photoelastic model and the actual turbine blade particularly exists in the difference of manufacturing accuracy in the dovetail region. The dovetail of the actual blade has very precise accuracy, say ±0.001 mm, furthermore it shows stress relaxation when it suffers high loading. While the photoelastic test remains elastic stress analysis for the given shaped epoxy models. Therefore one had better keep in mind that the photoelastic test would show relatively severe results than those in the actual blade.

Fig. 5 shows calculated cross-sectional mean



(a) Blade portion (b) Dovetail portion

Fig. 5 Cross-sectional mean centrifugal stress in actual turbine blade stress due to centrifugal force of the actual blade with 105% of designed rotating speed. The curve can be a reference for the discussion of appropriateness of the present photoelastic test results. Material of the actual blade is a Nickel base superalloy IN-100. Its tensile strength at room temperature is about 80 Kgf/mm^2.

Experimental Apparatus and Procedures

Centrifugal stress in photoelastic models is frozen while rotating under the condition of an appropriate temperature control of ambient with respect to time. The models, thereafter, are sliced so as to involve scheduled important sections. Photoelastic analysis is then applied to each slice.

Inside view of temperature controlled container with a rotating shaft driven by a motor outside is shown in Fig. 6. Epoxy resin models are attached to a turbine disc model as shown in Fig. 7. The blade models and the disc are confined to a casing which has no mechanical contact with the blade models. These models suffer little fluid pressure while rotating owing to the casing. Lower end of the shaft is supported with a bearing and a damper connected to a supporting frame as seen in Fig. 6. Temperature in the container is controlled with a heater set below a bottom plate and its electric control system.

Before experiments, temperature was checked in upside and downside of the casing under the same condition as experiments except for the absence of the blade models. The temper-

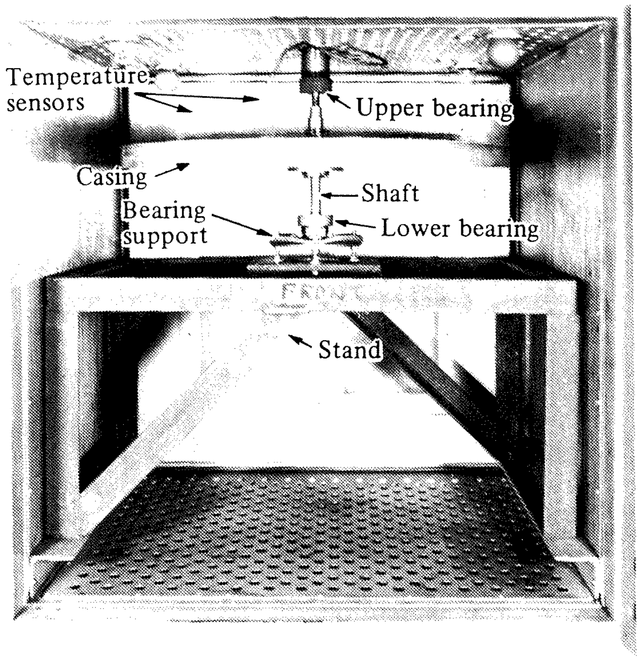


Fig. 6 Inside view of temperature controlled container with experimental rotating system

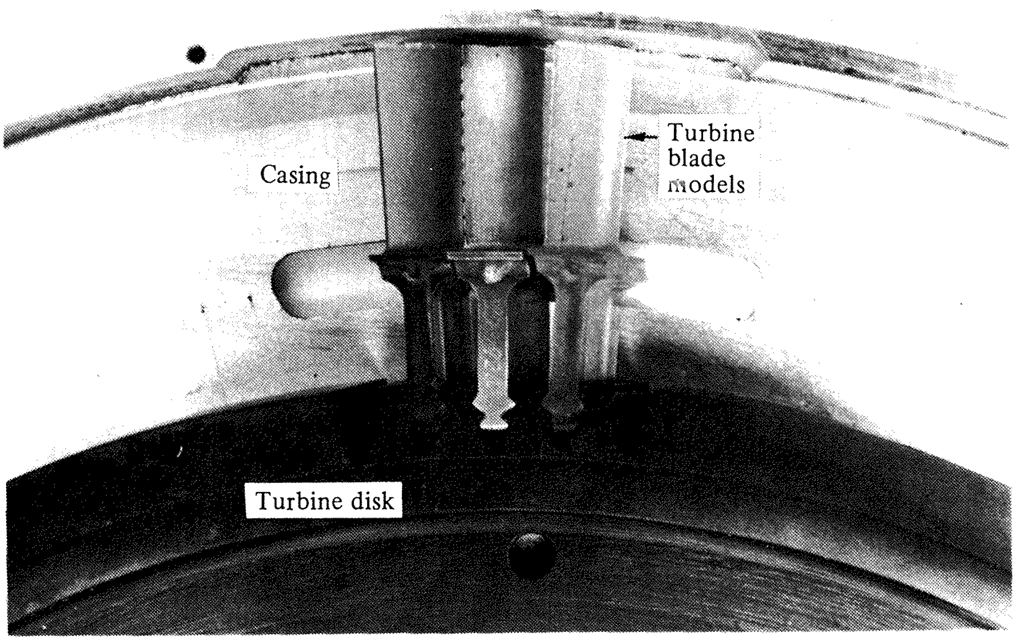


Fig. 7 Inside view of casing

ature difference was enough small to give uniform temperature to the whole blade models as long as the scheduled temperature control was observed. Rotating speed was measured with a photo-transistor detecting dark and bright stripes on the pulley connected to the shaft, and a pulse counter. Its pulse signals were converted to voltage at the same time and recorded by a pen recorder. Temperature was measured with Chromel-Alumel thermocouple and recorded by the other pen recorder.

Fig. 8 shows the results with the pen recorders. As shown in the figure, temperature was kept at 125°C for longer than two hours in order to give the epoxy models enough period to build up an elastic situation under a satisfying uniform temperature, then was reduced at a rate of 5°C/hour which had already been known as a well sufficient rate to the frozen stress method. Rotating speed of 1445 rpm was selected after various and careful considerations as follows. It should bring maximum fringe order from 8th to 10th at the maximum stress point which has well enough spacial resolution of stress and is still not so confusing density of fringes to be read. On the other hand, the thickness of slices are restricted due to a mechanical strength of the models while cutting with a saw but it should be as thin as pos-

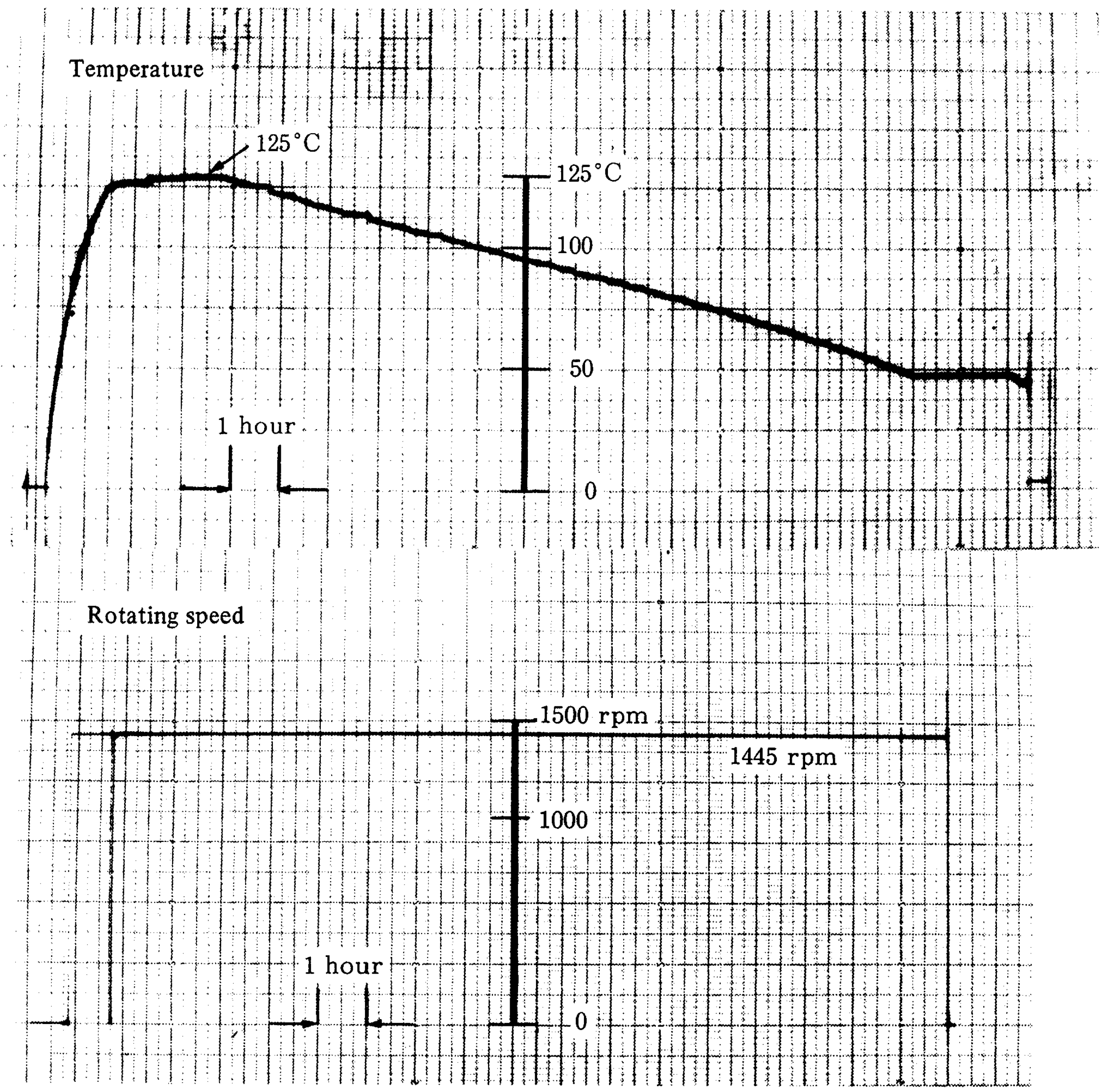
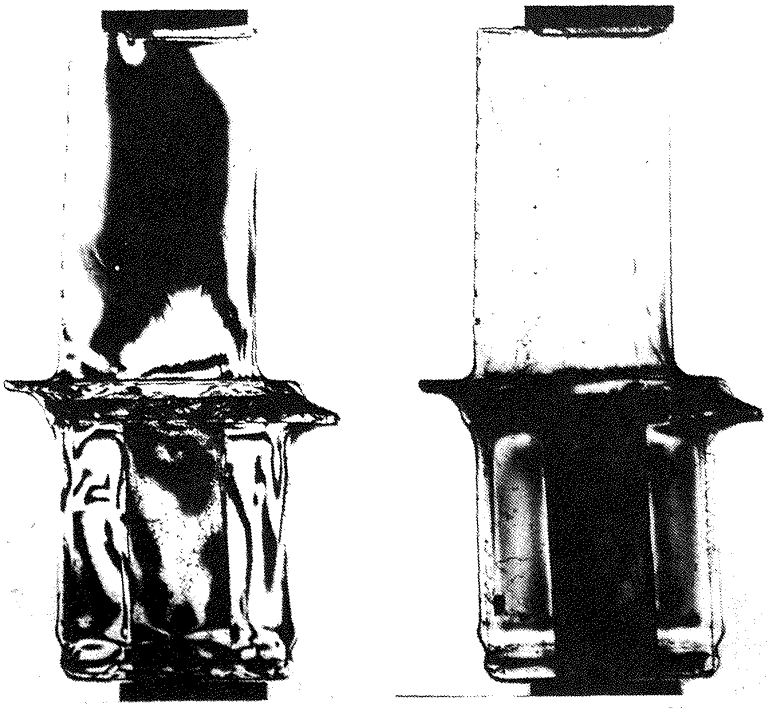


Fig. 8 Temperature and rotating speed variations in container during stress freezing

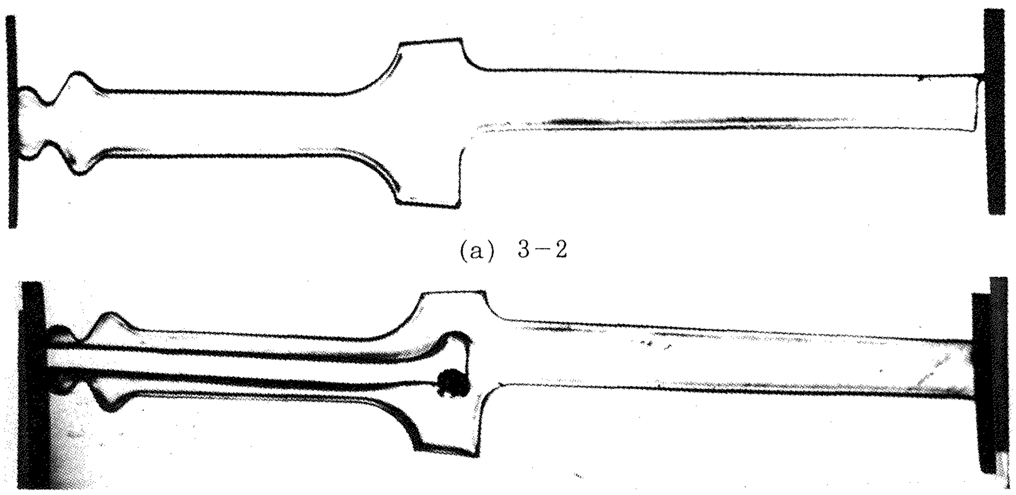
sible since the models are three dimensional. Thus about 3 mm in thickness was chosen. Therefore the rotating speed can be figured out from the thickness, anticipated maximum stress and photoelastic properties of the models. Finally the rotating speed should not cause a vibration of the test model total system. The resulting rotating speed has been satisfactorily stable as seen in the figure. Apparatus for a photoelastic analysis is of a transparent type and it has an effective visual field of 300 mm in diameter. A dipping bath is used in order to avoid light scattering from the surface of the models as usually introduced.

Annealing is required for all the models before analyses. Fig. 9 shows a result of annealing of the model (a). Temperature cycle of annealing is the same as that shown in Fig. 8. It can be seen that residual stress generated during manufacturing the model is extinguished completely by the annealing. Fig. 10 shows another results of annealing. The slices can also be annealed



(a) Before annealing (b) After annealing

Fig. 9 Annealing condition of blade model



(a) 3−2

(b) 6−1

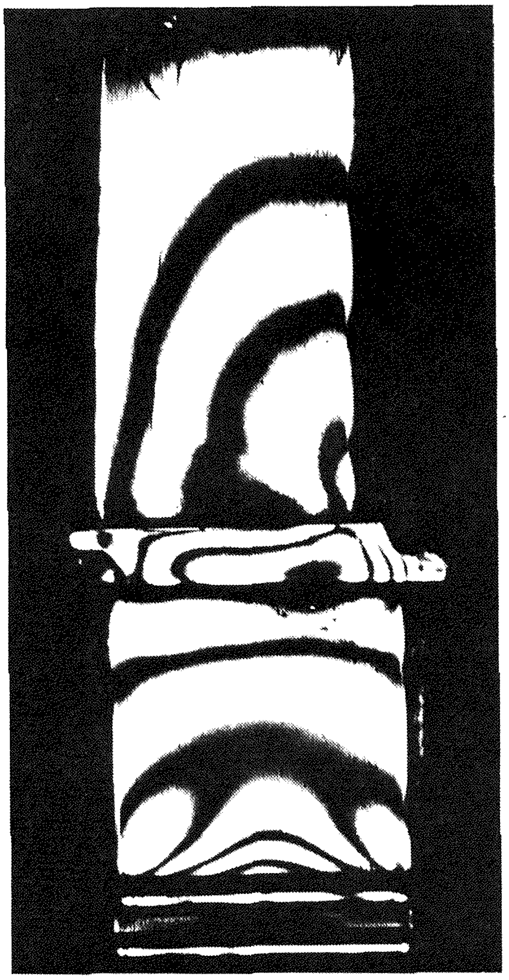
Fig. 10 Annealed slices (see Fig. 13)

satisfactorily. This was done after centrifugal stress analyses. It might safely be said that these all results prove the appropriateness of the present annealing condition and stress freezing procedure.

Results and Discussions

Fig. 11 shows isochromatic fringe patterns in the solid and hollow turbine blade models after stress freezing. Patterns in the blade part are almost the same since both are solid, while lower half patterns, those in the extended root, are different with each other. These patterns can be used in order to make sure whether the model is manufactured and the experiment has been done both satisfactorily or not. These patterns, therefore, should be observed before cutting.

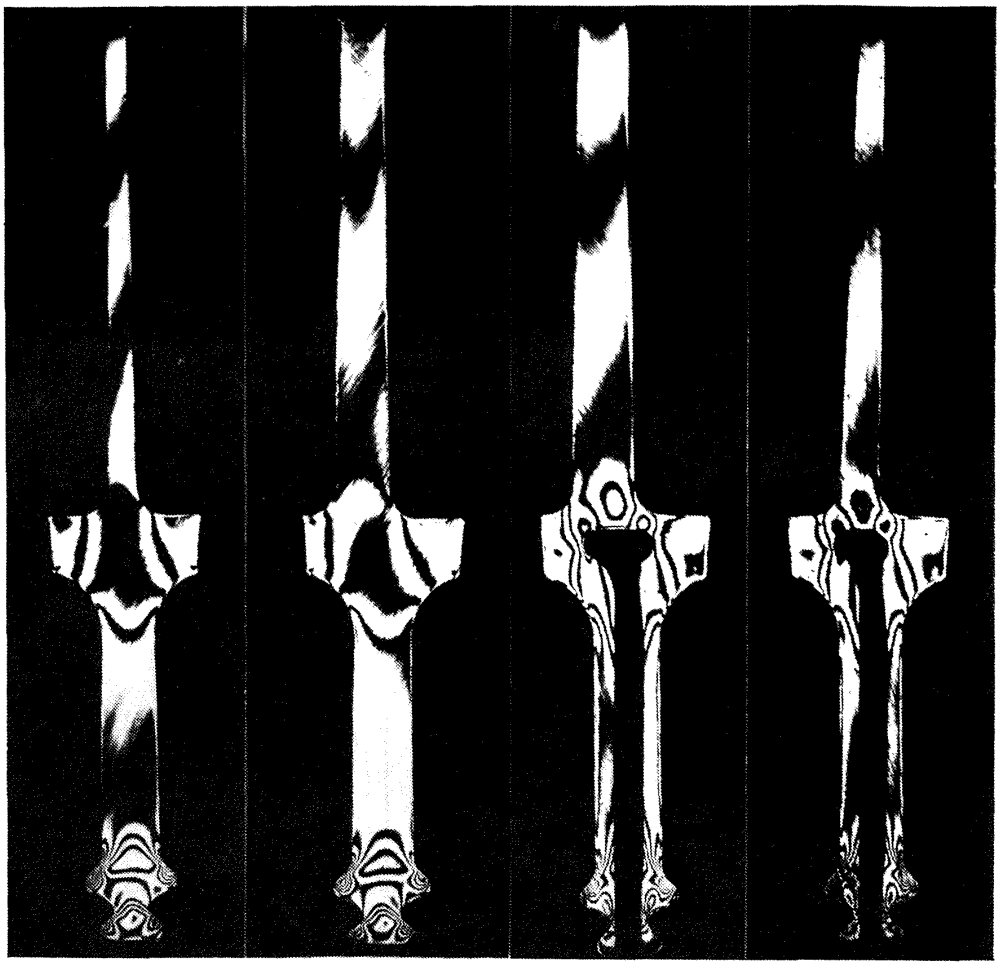
Fig. 12 indicates fringe patterns in the slices cut in the longitudinal direction both for the solid and hollow blades. The locations of the slices in the blade models are shown in Fig. 13 and they are the most important sections of the present study since they involve very thin thickness part around the coolant passage for the hollow blade model. The slices (a), (b) and (c), (d) show fairly similar patterns to each other, respectively. This means that stress distributions in the mid region are rather uniform in the thickness direction of the slices both for the solid and hollow blade models. On the other hand, the slices (a), (d) and (b), (c) make the comparison possible on the difference in stress distributions between the solid and hollow blade since each pair is almost of the same relative location, re-



(a) Solid blade model

(b) Hollow blade model

Fig. 11 Isochromatic fringe patterns of blade models



(a) 3−1 (b) 3−2 (c) 6−1 (d) 6−2

Fig. 12 Fringe patterns of sliced blade models

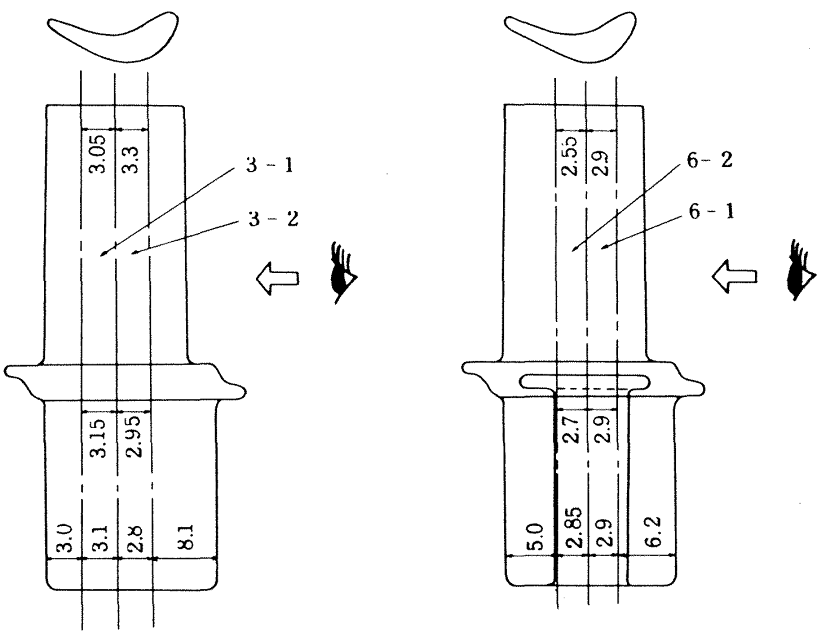


Fig. 13 Position of slice models in blades (Numerals in mm)

spectively.

Fig. 14 shows distributions of fringe order for the principal part of the slices (b) 3-2 and (c) 6-1 in Fig. 12. As a matter of course, there exist dense distributions of fringe surrounding a coolant chamber in the platform region for the hollow blade while it remains relatively lower order of fringe in the same region for the solid blade. Descriptions of stress estimates are given in the following paragraph. The highest order of fringe locates at the point in the dovetail where the blade models hit on the turbine disc model both in the solid and hollow blades. In the solid blade, there are four touching points and thus the centrifugal force of the blade is dispersed moderately and consequently the highest order of fringe is lower than that in the hollow blade. As shown already in Fig. 3, the mid region of the

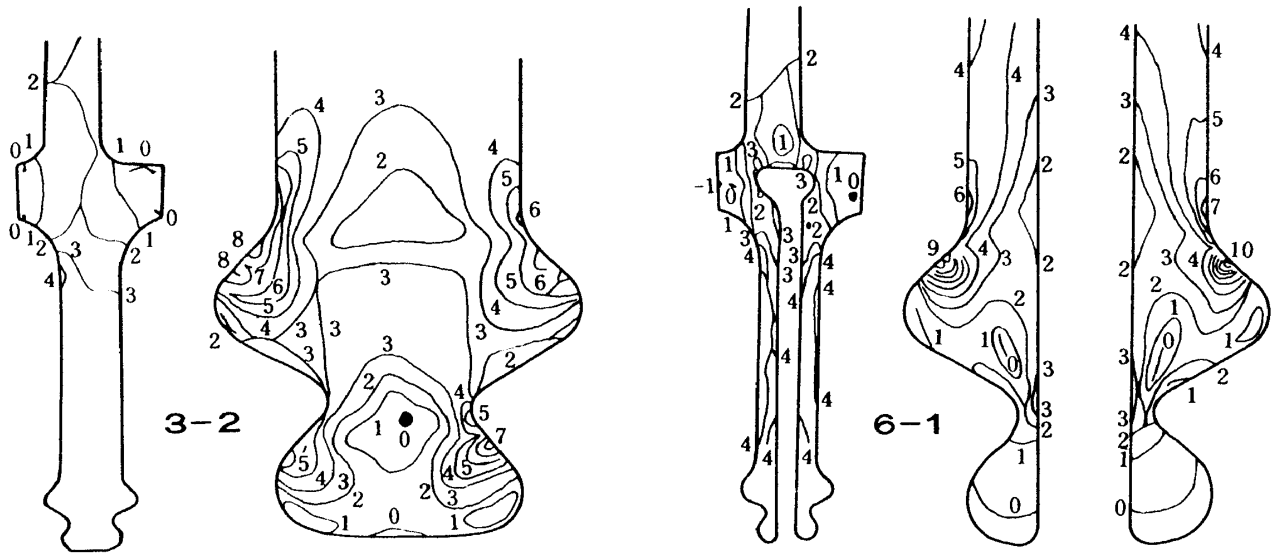


Fig. 14 Fringe order distributions in principal part of slice models

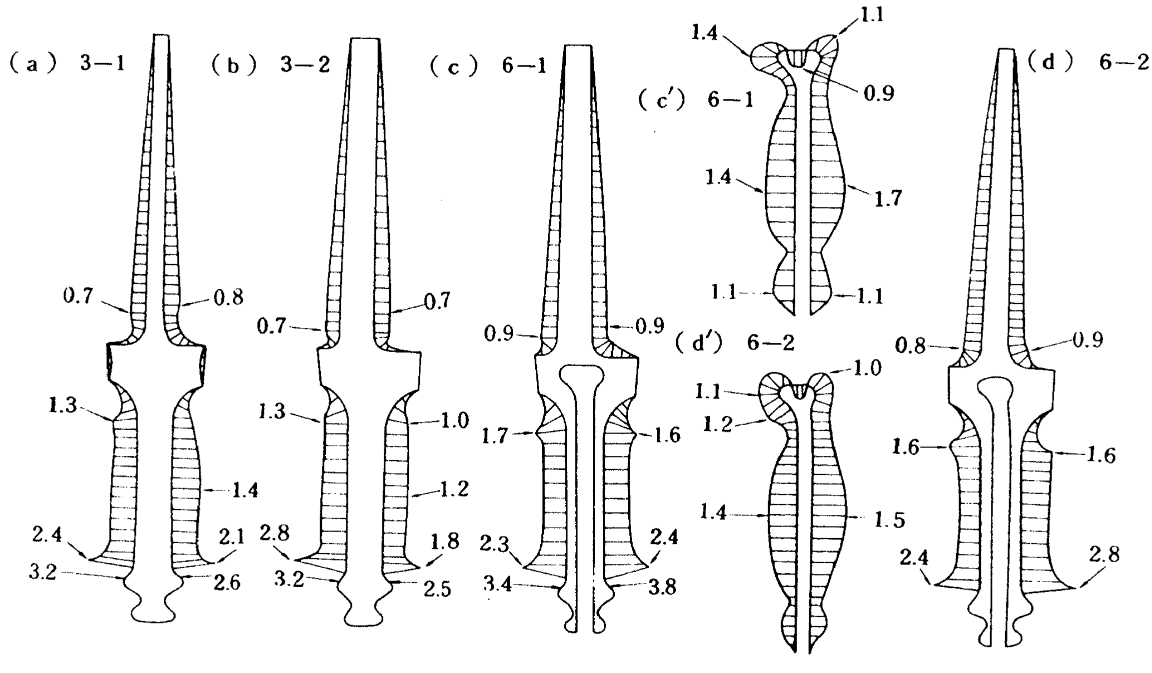
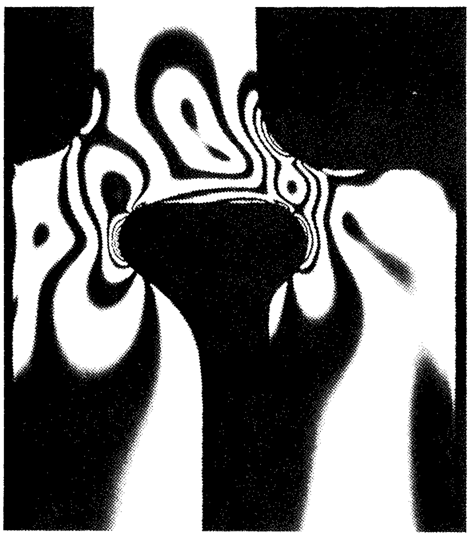


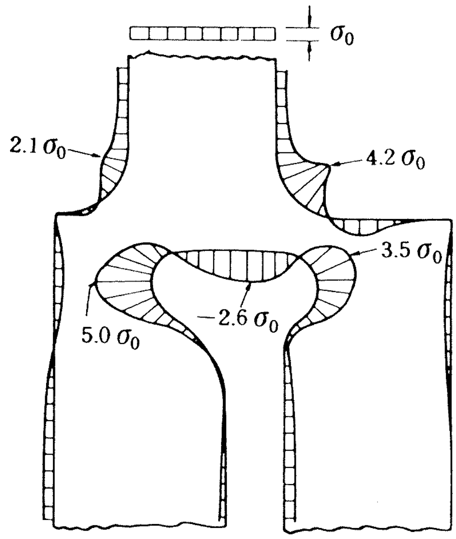
Fig. 15 Surface stress distributions on slice models (Numerals in fringe order/unit thickness)

extended root in the hollow blade tends to shrink while manufacturing, furthermore the dovetail and the extended root of both sides of the coolant passage receive distortion toward a center due to the centrifugal force. Therefore, it might be natural that there are only two points hitting on the turbine disc for the hollow blade, although this would not be quite true for the actual turbine blade since it should have much more precise dimension both in the cross section as shown in Fig. 3 and the dovetail. Distribution of load in the dovetail region is a little bit unbalanced on the right and the left hand sides, but it seems not so serious as to make analyses meaningless.

Fig. 15 shows distributions of the fringe order per unit thickness proportional to tangential stress along the surfaces of the slice models which have been discussed so far. As already described in the preceded paragraph, the stress at the outer surface around the platform is not so high for the hollow model. While the stress at the inner surface in the platform region is less than that at the outer surface in the same model. The maximum value of fringe order among those around the relevant region is 1.7, which is corresponding to the tensile stress of 29.3 Kgf/mm^2 in the actual turbine blade under the condition given in Fig. 5.*** This magnitude is far less than any relative maximum seen at the outer sur-



(a) Fringe patterns



(b) Surface stress distributions

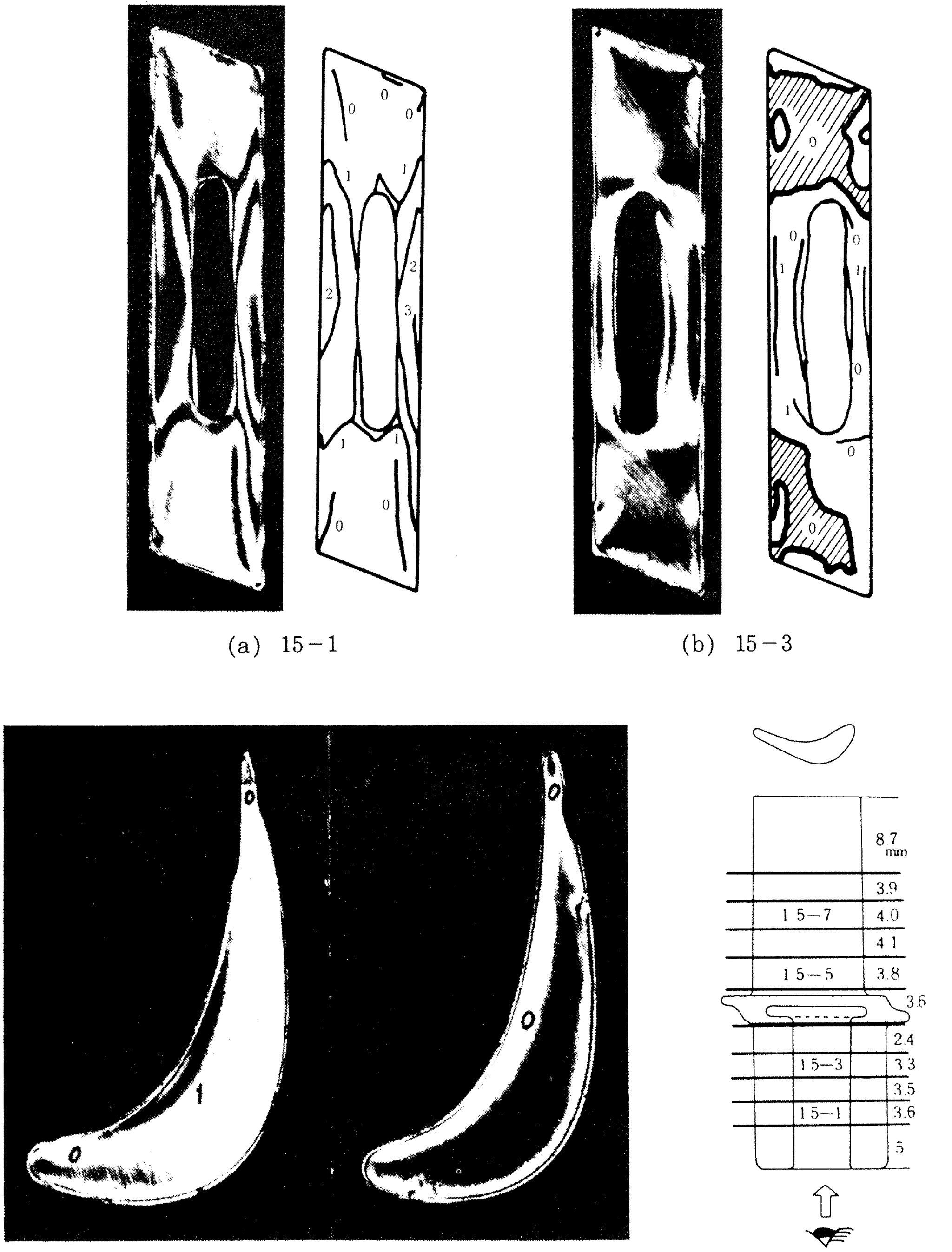
Fig. 16 Two-dimensional photoelastic test under tensile condition

***Conversion

The conversion from the fringe order per unit thickness to the stress in the actual turbine blade is done as follows in the present study. The centrifugal stress in the actual turbine blade is calculated in advance as shown in Fig. 5. The reference section is selected at the distance of 18.6 mm downward from the blade tip where cross-sectional mean fringe order in the photoelastic model can be figured out easily and accurately. At the selected section, we have 0.517 in the fringe order per unit thickness for the photoelastic model and the tensile stress of 8.9 Kgf/mm^2 for the actual blade. Thus the resulting conversion factor is 17.215. According to this value, the photoelastic sensitivity in the present model is to be 38.3 fr.mm/Kgf. The photoelastic sensitivity is calibrated separately for two discs made from the same material as the blade model and resulting mean value is 37.7 fr.mm/Kgf. Therefore the conversion factor can be of an accuracy more than 98%. As a reference, the stress in photoelastic model is essentially calculated from fringe order, photoelastic sensitivity and thickness.

face in the dovetail region, and it is considered well permissible. At the section just up the dovetail, there are relative maximum points. The highest value among those is 2.8 (48.2 Kgf/mm^2) and it is observed both for the solid and hollow blade models. In this sense, there is no disadvantage to provide the coolant passage in the present case. This order of magnitude, however, is not so an easy one to guarantee that a turbine blade survives without any serious damage for a scheduled life. Thus it is required to select blade material carefully. As for the Nickel base alloy IN-100 introduced in the present research project, these should not be a problem.

Fig. 16 indicates the result of two-dimensional photoelastic test under the tensile condition to the model with a similar shape to the slice 6-1 in Figs. 12−15. σ_0 in Fig. 16 designates a



(a) 15−1 (b) 15−3

(c) 15−5 (d) 15−7

Fig. 17 Fringe pattern and fringe order distributions at lateral cross-sections of hollow turbine blade model mean tensile stress at the uppermost section of the model. This has been done in the earlier work 4) in which the appropriate shape and location of the coolant chamber in the platform region of a blade have been surveyed. The result shown in the figure is considered at least one of the best among models tested in view of structural strength. Comparing this with the corresponding results (c) in Fig. 12 and (c), (c') in Fig. 15, the trend of fringe pattern and tangential surface stress distribution are considerably similar. However, stress concentrations in the two dimensional test are more intense than those in the present test, especially at the locations with a relative maximum curvature. This fact tells us clearly that two-dimensional tensile test brings relatively severe stress anticipation to rotating turbine blades but it is still effective and very helpful as a preliminary test because of easiness of the test.

Finally, Fig. 17 shows the fringe pattern and fringe order distributions at various lateral cross sections of the three dimensional hollow turbine model. Cross-sectional mean stress is obviously decreasing as the section is of upper one. Absolute stress values are pretty small compared to those in the longitudinal sections shown already. There exists no compressive stress in all the sections shown in the figure. This is another noticeable feature of the results.

CONCLUDING REMARKS

(1) A new molding method of three-dimensional hollow photoelastic model was developed. Disinctive features of the method are as follows. As for formation of a core with required hollow shape, low melting point material like wax should be used, furthermore thin copper plating onto the core material is required. Patterns both for the core and the model itself are made of silicone rubber. Molten epoxy resin as photoelastic material is poured and hardened in the pattern, then the core made of wax is excluded with hot air, and finally thin copper layer is dissolved with corrosive, $FeCl_3$. The present method enables three-dimensional complicated and fine hollow shape to be formed in a model as far as uniform thin copper plating on the whole surface of core is possible.

(2) Centrifugal stress analysis has been performed for air cooled turbine blade models to which the new method above mentioned was applied. The frozen stress method was introduced for the analysis. The conditions of stress freezing appeared to be satisfying by several kinds of inspection. Principal results obtained from the analysis are described as follows.
Stress distributions in longitudinal and lateral sections of the turbine blade models were obtained and thus relative maximum values and their locations were made clear. The maximum stress in the hollow blade model appeared in the upsides next to the dovetail outer surface and was of the same order of magnitude as that in the solid blade model with similar outer shape. Compared to this maximum stress, the other relative maximum values seen on the outer surface around the platform and on the corner of coolant passage inside of the blade were relatively small, and thus they would be permissible to be designed. The highest stress was practically observed in the dovetail region for the present analysis, however it should be excluded from the discussion because the epoxy resin models introduced in the analysis were neither formed so precisely as the actual turbine model nor suffered stress relaxation. The three-dimensional stress analysis as the present study brings us far more credible data than the two-dimensional test, but it requires rather high technology.

ACKNOWLEDGEMENT

As for the manufacturing method, the authors should express their sincere appreciation to the members of the Photo Cutting Laboratory Co., Ltd. for their unique contribution. Acknowledgements are also made to the Komatsu Howmet Co., Ltd. and the Central Engineering Laboratories, Nissan Motor Co., Ltd. for their collaboration during the early stage survey of the study.

The discussions of the experimental apparatus with Dr. T. Miyachi, Mr. T. Ikeda and Mr. Y. Matsuda, Aeropropulsion Division, NAL should also be acknowledged.

REFERENCES

(1) Y. Akoh and M. Hashimoto; Technique of Mold in Photoelastic Model and its Applications, Non-Destructive Inspection, 20-7, 1971, pp. 377 ~ 384, (in Japanese).

(2) T. Kunio, M. Kuramoto and T. Koizumi; Stress Analysis of Pressure Regulating Valve by Three Dimensional Photoelastic Tests, Lecture Meeting Preprints, JSME, 700-3, 1970, pp. 181 ~ 184, (in Japanese).

(3) K. Takahara, et. al.; High Temperature Turbine Researches at the National Aerospace Laboratory, Part 1-3, Jr. of GTCJ, 2-6, 7, 8, 1975, (in Japanese).

(4) K. Matsusue, R. Hashimoto and M. Yonaiyama; Two Dimensional Photoelastic Tests of Air Cooled Turbine Root Sections, NAL TM-276, 1975, (in Japanese).

TECHNICAL REPORT OF NATIONAL
AEROSPACE LABORATORY
TR-427T

航空宇宙技術研究所報告427T号（欧文）

昭和56年5月発行

発行所　航空宇宙技術研究所
東京都調布市深大寺町1880
電話武蔵野三鷹（0422）47-5911（大代表）〒182
印刷所　株式会社　三興印刷
東京都新宿区信濃町12　三河ビル

Published by
NATIONAL AEROSPACE LABORATORY
1,880 Jindaiji, Chōfu, Tokyo
JAPAN

Printed in Japan