Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45352

A RESIDUAL STRESS MEASUREMENT TECHNIQUE FOR TURBINE BLADE DOVETAILS

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ABSTRACT

In aeroengines or industrial gas turbine blades, it is important to estimate the residual stresses at the surface of the blade root to ensure the structural integrity of the part. Most turbine blades are investment cast superalloys and it is difficult to apply the standard X-ray diffraction method to measure the residual stresses, because of the presence of a coarse grain size in these parts.

Therefore a special technique was adopted to enable an estimate of the residual stresses at the surface of the turbine blade dovetail, which is a typical feature of the blade root. This method consists of a combination of the curvature method and the FE analysis. After obtaining a good agreement between the results using this method with the standard X-ray diffraction method in wrought Alloy 718 that possesses a very fine grain size, the residual stress distributions in the subsurface region of cast turbine blade dovetails were successfully obtained.

1 INTRODUCTION

The dovetail of a turbine blade is subjected to high centrifugal loads due to the blade mass and the gas forces. Meanwhile, at production stage the manufacturers try to avoid machining processes if at all possible for cost reduction, but in the case of dovetails, machining is inevitable because of the strict dimensional tolerances required for structural reasons. Therefore residual stresses are essentially generated in the subsurface region during machining, where tensile stresses can potentially have an adverse effect on the structural integrity of the part, especially under fatigue loading conditions. Shot-peening is thus applied to the dovetail surface to forcibly induce compressive residual stresses, but in some cases it may not be employed for cost reduction reasons. In such cases, it is required that the residual stresses at the dovetail surface are evaluated to ensure their compressive nature after machining and appropriate adjustments to the machining process may be necessary in some situations. For this reason, a reliable method is required to measure the stresses in the subsurface region of the dovetail after machining is complete.

To measure the residual stresses, especially those in the very shallow regions beneath the surface, the X-Ray diffraction method is generally adopted. However, it cannot be applied to the coarse grained turbine blade materials. The standard X-ray diffraction method ($\sin^2 \phi$ method) uses the least square method to develop a relationship between the grain angles and the diffraction angles picked up from many grains within the X-ray spot to quantify the residual stresses. Hence the application of this method is essentially limited to the polycrystalline materials possessing a fine grain size and it cannot be readily applied to coarse grained turbine blades. The blades are manufactured out of conventionally cast or directionally solidified superalloys, both of which possess very coarse grain sizes, or single crystal superalloys that only possess one crystal grain. The X-ray diffraction method cannot be applied in these cases.

The other reliable methods for residual stress measurement are the hole drilling method, the curvature method, the neutron diffraction method etc. The hole drilling method needs enough space to place the gauges around the drilling hole, and it is almost impossible to apply to turbine blade dovetails. The neutron diffraction method requires access to very specialized facilities and the cost for using them is prohibitive. Therefore the curvature method, which is a type of stress relief method, is deemed to be the most appropriate for the application at hand. Kovac[1] has provided the details of the procedure and examples of its application. However, the applications shown by Kovac are limited to the plate configurations and the formulations presented are only applicable for the case where the thicknesses of all electrochemically removed layers are equal. As a result, the in situ method shown by Kovac is difficult to apply in the case of the turbine blade dovetails.

Therefore a special method which has no limitation in terms of the parts' configuration and the removed material thicknesses was adopted to enable an estimate of the residual stresses in the subsurface regions of turbine blade dovetails. It consists of the measurement procedure of the curvature method using the specimen that is cut off from the dovetail and FE analysis procedure to estimate the stress distribution through the thickness of the dovetail.

2 RESIDUAL STRESS MEASUREMENTS WITH WROUGHT ALLOY 718 SPECIMEN

As a first step, to verify the validity of this method, it was applied to the wrought Alloy 718, the grain size of which is fine enough to measure the residual stress using the X-ray diffraction method and the results of the two methods were compared to each other. All procedures involved in the present method are described in detail in the following sub-sections.

2.1 Measurement method

2.1.1 Specimen

Shot-peening was first applied to the surface of a block of wrought Alloy 718 material (intensity was 8A), then the specimen was cut out from the block using EDM (wire cut). The EDM surface of the specimen was polished gently with an abrasive paper to eliminate any processing effects. Fig.1 shows the configuration of the specimen and the fabrication procedure.

2.1.2 Measurement procedure

An outline of the measurement procedures is schematically shown in Fig.2.

(1) 1st step : Preparation

Measure the initial bending deformation of the specimen (arch height) using a surface roughness tester and measure the surface residual stresses using the X-ray diffraction method.

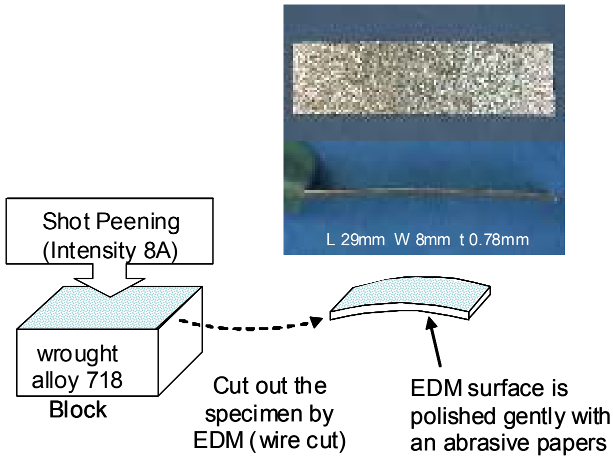


Fig.1 Specimen

Details of the X-ray diffraction measurement technique are tabulated in Table.1. This was followed by attaching a strain gauge on the reverse side of the shot-peened surface in the longitudinal direction, and by installing the wiring and covering them by air-drying silicone rubber to protect them from electrochemical polishing. Fig.3 shows the specimen with strain gauge prior to covering with the silicone rubber.

(2) 2nd step : Electrochemical removal

Remove a certain material thickness from the shot-peened surface by electrochemical polishing. Fig.4 shows the electrochemical polishing process.

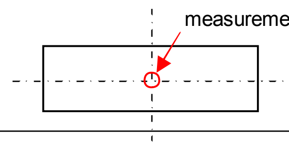
(3) 3rd step : Strain and residual stress measurement

Measure the strain gauge based strain and the X-ray diffraction based residual stresses of the electrochemically polished surface after each material removal step.

The 2nd and 3rd steps are repeated until the residual stresses measured using the X-ray diffraction method and the bending deformation (arch height) become nearly equal to zero. Measured stresses using the X-ray diffraction method at each material removal step are assumed to represent the values present at the top surface of the specimen.

Table 1 Details of the X-ray diffraction measurement

- Stress measurement method : $\sin^2\psi$
- X-ray beam : Cr (Ka)
- Diffraction angle 2θ : 133deg.
- Measurement direction : longitudinal and widthwise.
- Measurement point : center of evaluation surface.



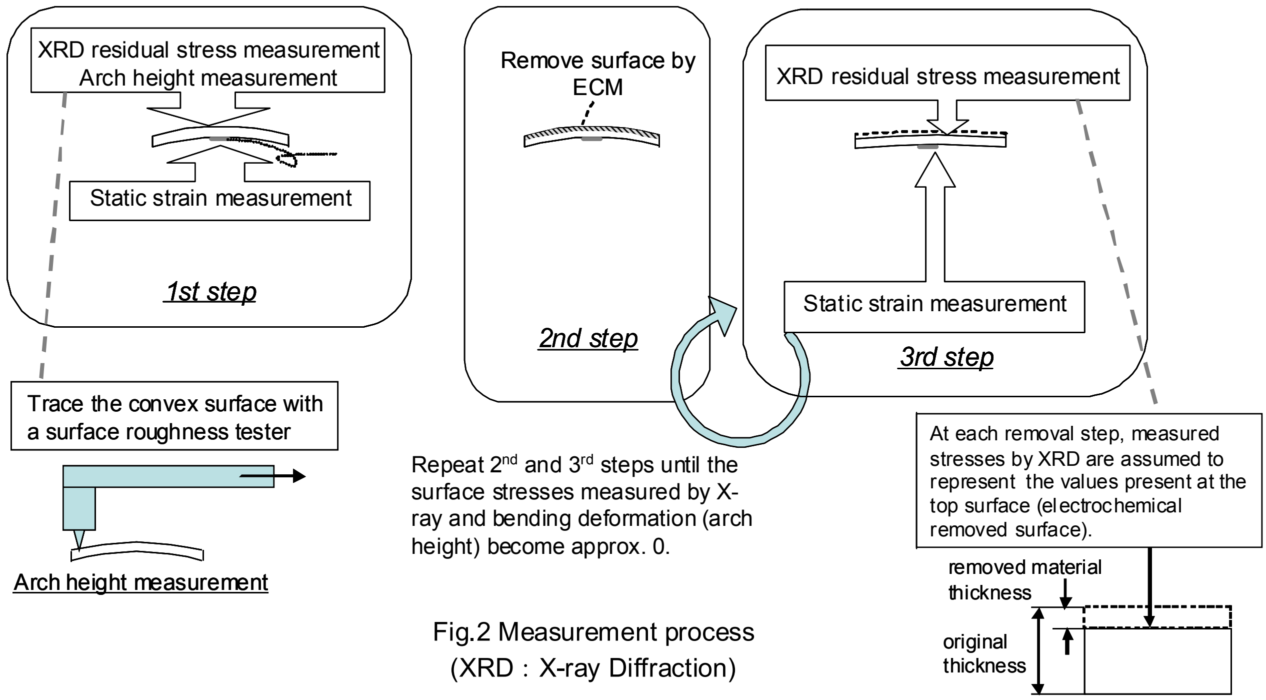


Fig.2 Measurement process
(XRD : X-ray Diffraction)

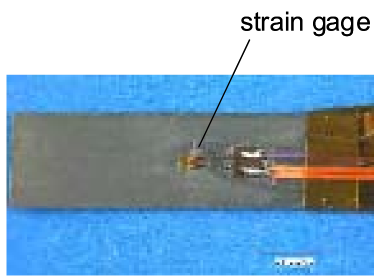


Fig.3 The attachment of a strain gauge

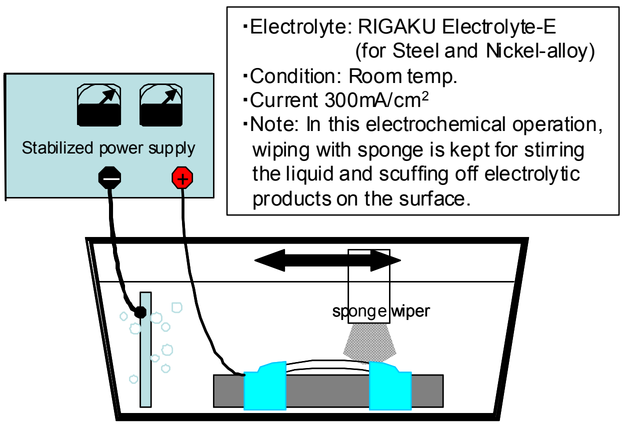


Fig.4 The electrochemical process

2.2 Measurement results

The measured residual stresses and strain at each removed material thickness are shown in Fig.5. The initial bending deformation (arch height) values are tabulated in Table 2.

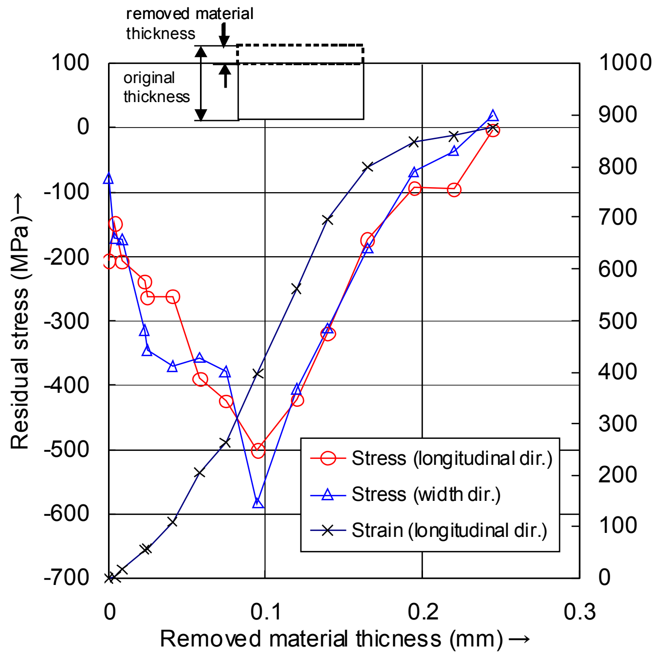


Fig.5 Result data: strain, residual stress as a function of removed material thickness

2.3 Estimation of residual stress distribution using the FEA

The residual stress distribution through the thickness of the specimen was estimated by the FE analysis to match the strain measurement results presented in section 2.2.

2.3.1 FE Model

The 3D FE models of the 0-th ~ (N-1)-th described in section 2.3.2(2) were constructed taking into account the thickness of each electrochemically removed layer. Fig.6 shows the 0-th model (whole model), which is the 1/4 of the whole specimen using geometric symmetry. The thicknesses of the models before and after all the steps of electrochemical material removals were those measured with the micrometer and the thickness after each electrochemical material removal step was estimated using the dwell time versus the material remaining correlation of the electrochemical polishing technique.

Thermal stresses were virtually applied to simulate the residual stresses and temperature boundary conditions were thus assigned individually to each layer.

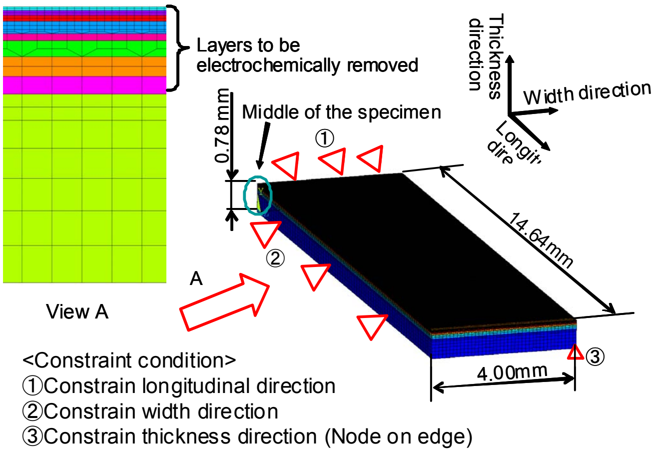


Fig.6 3D FE model

2.3.2 Analytical procedure

The residual stress distribution through the thickness was estimated using the following procedures as shown schematically in Fig.7

(1) Calculate the difference $\Delta\varepsilon_i (= \varepsilon_N - \varepsilon_i)$ where ε_i is the measured strain in the longitudinal direction after removal of the 1-st to the i-th layers from the top surface (i=0 to N-1). N is the total number of electrochemical removed layers and ε_N is the measured strain after the final electrochemical material removal step. 0 means no removed layer and ε_0 is equal to zero.

(2) Construct each i-th model (i=0 to N-1) of which layers from the first to the i-th are removed from the whole model shown in Fig.6. (the 0-th model means the whole model with no layer removed.)

(3) Ascribe a temperature to each (i+1)-th layer using the i-th model so as to match the strain of the FE analysis result to the $\Delta\varepsilon_i$ that is the measurement result. The temperature of each layer is assumed to be uniform throughout the layer.

Compute the residual stresses at the top surface of the i-th model to compare with the stresses measured by the X-ray diffraction method.

This procedure is executed from i=N-1 to 0 to decide each layer temperature serially from the bottom to the top layer.

(4) Obtain the residual stress distribution of the specimen and the bending deformation (arch height) in the initial condition (before electrochemical material removal) by conducting the whole model analysis with each layer temperature ascribed in step (3).

2.3.3 Results

Fig.8 shows the residual stresses in the middle of the top surface of the specimen after each material removal step, which are estimates using the present method and those measured using the X-ray diffraction method respectively. The differences of the maximum compressive stresses between the two methods are about 5% in the width direction and about 20% in the longitudinal direction. Table 2 shows the amount of initial bending deformation (arch height) estimated by the present method (FE analysis result) and the actual measurement. (The measurement was confined to the range shown in Fig.10 due to the limitation of the measurement tool.) The difference is about 13% (longitudinal direction).

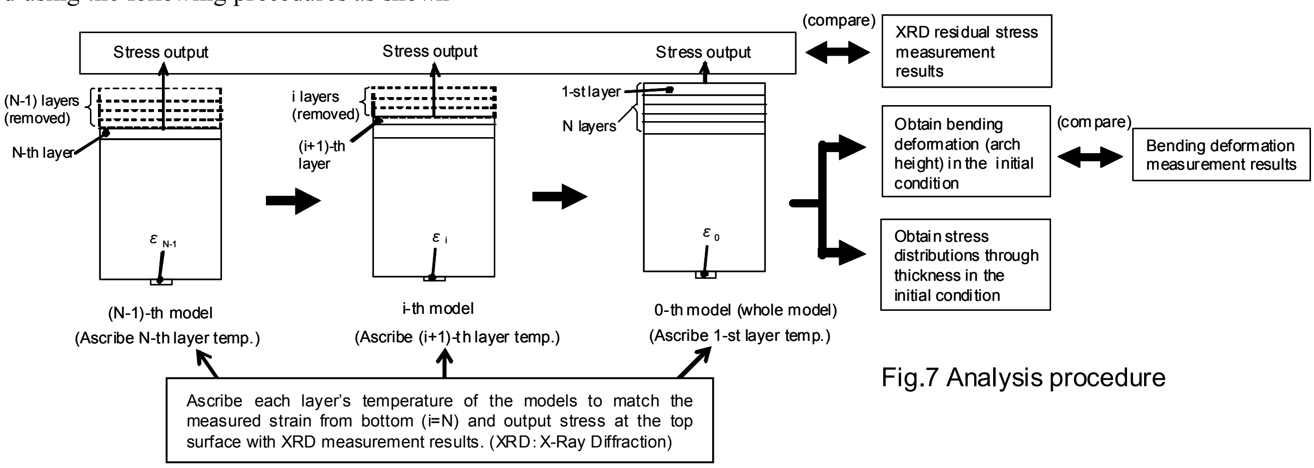


Fig.7 Analysis procedure

Fig.9 shows the residual stress distributions through the thickness in the middle of the specimen and Fig.10 shows the bending deformation in the initial condition based on the FE analysis results of the whole model.

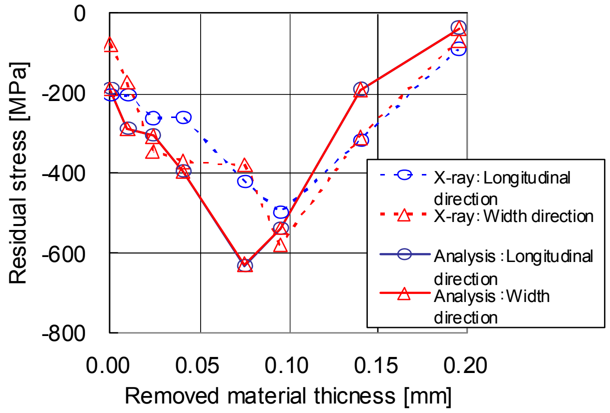


Fig.8 Residual stresses in the middle of the top surface of the specimen (normal stress)

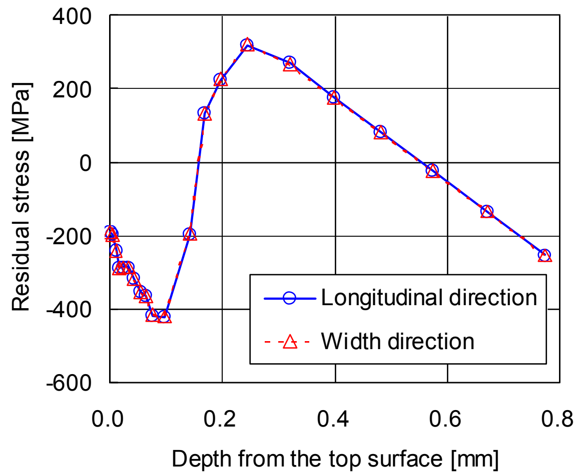
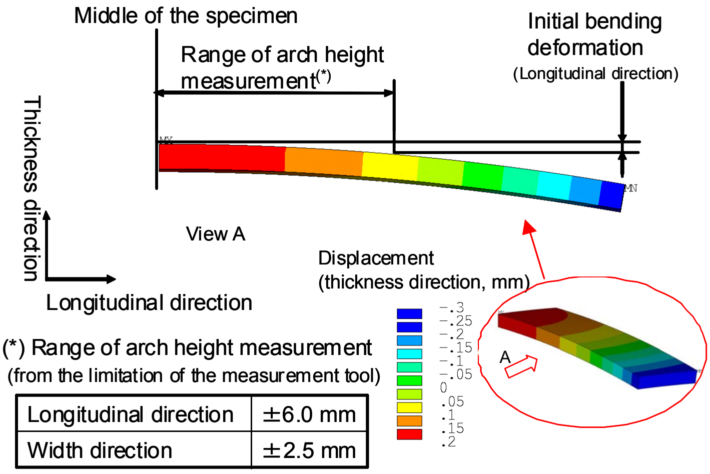


Fig.9 Residual stress distribution through the thickness in the middle of the specimen (normal stress)



(*) Range of arch height measurement
(from the limitation of the measurement tool)

Longitudinal direction	±6.0 mm
Width direction	±2.5 mm

Fig.10 Initial bending deformation by FE analysis

Table 2 Initial bending deformation (arch height)

Longitudinal direction		
Measurement [mm]	Analysis [mm]	Difference [%]
0.080	0.071	13%

Width direction		
Measurement [mm]	Analysis [mm]	Difference [%]
0.014	0.012	14%

2.4 Discussion

(1) As shown in Fig.8, the residual stress profiles tend to be in good agreement using the results of the present method and the X-ray diffraction method. The quantitative differences are mainly caused by the following experimental and analytical limitations.

(a) The results of both methods inherently possess certain amount of measuring error caused by different variables.

(b) The stresses measured by the X-ray diffraction method are confined to the very local area of the surface, hence the results are susceptible to the effect of nonuniformity of the material microscopic texture and the local variation in the residual stress distribution itself. In contrast, the results of the present method represents the macroscale averaged stress distribution.

(c) In the present method, the temperature of each removed layer is assumed to be uniform in the analytical model used to compute the residual stresses. As a result, the calculation essentially contains a discretization error.

In conclusion, it is considered that reasonable outputs can be obtained by the present method for estimating the residual stress distribution of the specimen.

(2) As shown in Fig.9, tensile stress region exists in the mid thickness and it becomes compressive towards the bottom of the specimen. This occurs due to the bending stress distribution that is generated to balance the compressive residual stress at the top surface and it becomes noticeable because the specimen thickness is very thin.

(3) It should be noted that the stress values measured in the thickness direction after each electrochemical removal step using the X-ray diffraction method are different from the original residual stresses through the thickness in the initial condition (before electrochemical removal of the material). The difference is clearly discernible upon comparing the results in Fig.8 and Fig.9 in the range of 0 ~ 0.2mm depth from the top surface. The present method enables an estimate of the original stress distribution using the FE model of the specimen in the initial condition and it is one of the significant advantages of this method.

3 ESTIMATION OF RESIDUAL STRESS OF TURBINE BLADE DOVETAIL

The present method was applied to the actual turbine blade dovetails that were in “shot-peened” and “as machined (not shot-peened)” conditions respectively. The residual stress distributions of these dovetail specimens were estimated and further verified.

3.1 Measurement method

3.1.1 Specimen

Specimens were cut out from the actual turbine blade dovetails manufactured out of a cast Ni-based superalloy. Both “shot-peened” (intensity was 8A) and “as machined” specimens were used. Fig.11 shows a typical specimen configuration along with their fabrication procedure. The EDM surfaces of both specimens were polished gently with an abrasive paper to eliminate any processing effects as described in section 2.1.1.

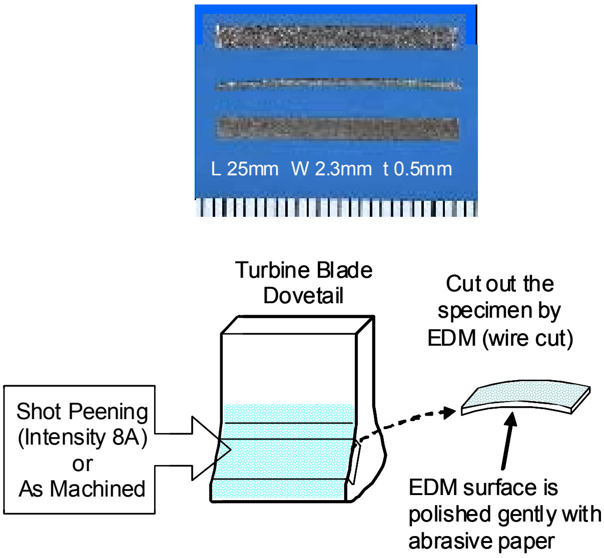


Fig.11 Specimen

3.1.2 Measurement procedure

The measurement procedures were the same as described in section 2.1.2 except no X-ray measurement technique was used. The 2nd and 3rd steps were repeated until the measured strain values were saturated and bending deformation (arch height) was approximately equal to zero.

3.2 Measurement results

The measured strains after each material thickness removal step are shown in Fig.12. In the case of the “as machined” specimen, the strain measurement was not possible beyond the last point shown in the graph as a result of the gauge wiring disconnection. However, at the last point in the graph the bending deformation was nearly equal to zero and the strain was thus judged to be saturated.

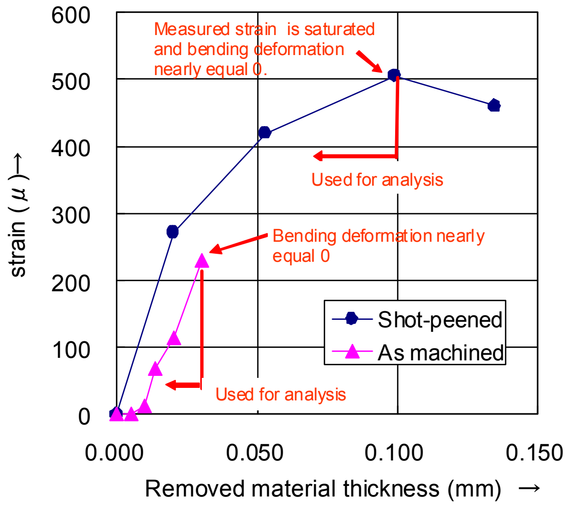
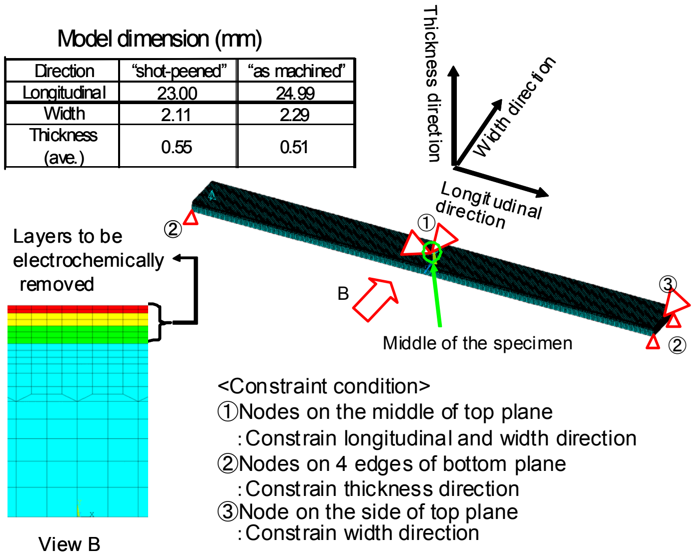


Fig.12 Result data: strain at each removed material thickness

3.3 Estimation of residual stress distribution of specimen

3.3.1 FE model

The 3D FE models of the 0-th ~ (N-1)-th (the definitions are the same as those given in section 2.3.2) for the“shot-peened” and the “as machined” specimens were constructed to estimate their residual stress distributions. The 0-th model (whole model) for the “shot-peened" case is shown in Fig.13.



Direction	“shot-peened”	“as machined”
Longitudinal	23.00	24.99
Width	2.11	2.29
Thickness (ave.)	0.55	0.51

Fig.13 3D FE model (shot-peened)

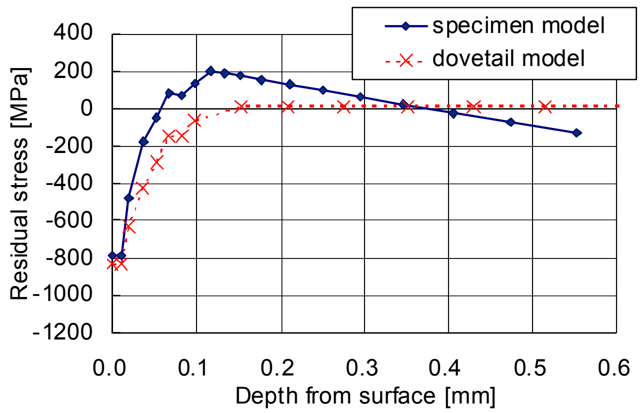
The FE models were constructed to take into account the thickness of each electrochemically removed layer in the same way as that described in section 2.3.1. The dovetail specimen thicknesses varied with the specimen locations, and the FE models were not thus symmetric.

3.3.2 Analytical procedure

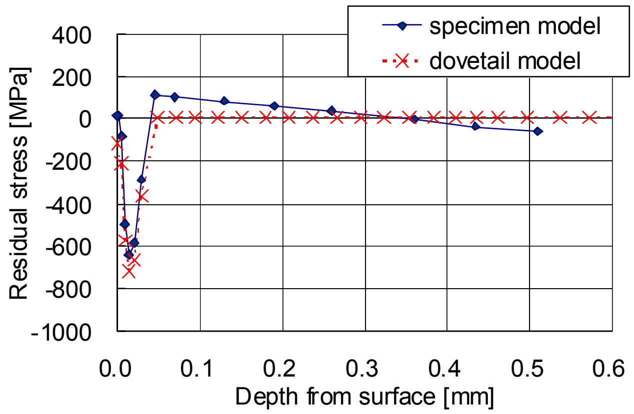
The FE analysis procedures used were the same as those described in section 2.3.2 except elastic-plastic analyses were conducted. In addition, the output of the residual stresses at the top surface of each i-th model was not considered because no X-ray stress measurement results were available for comparison.

3.3.3 Results

Figure 14 ("specimen model") shows the residual stress distributions in the middle of the specimen along the thickness direction for both "shot-peened" ((a)) and "as machined" ((b)) condition based on the results of the whole model analyses.



(a)"shot-peened" model



(b)"as machined (not shot-peened)" model

Fig.14 Residual stress distribution of specimen model and dovetail model

specimen model : shows normal stress in longitudinal direction in the middle of the specimen
dovetail model : shows normal stress in dovetail axial direction in the middle of the dovetail plane (Fig.15)

3.3.4 Discussion

The residual stresses in the subsurface region of "as machined" specimen are also compressive although their magnitude is lower and their distribution is shallower than the "shot-peened"specimen. This result was obtained only on one blade sample, and it cannot be generalized that the residual stresses at "as machined" surfaces are always compressive.

3.4 Estimation of the residual stress distributions in the dovetail

The residual stress distributions in the dovetails in the original product condition were estimated by FE analysis using the results presented in section 3.3.

3.4.1 FE model

The 2D FE models for the "shot-peened" dovetail and the "as machined" dovetail were constructed to estimate the residual stress distributions.

Their mesh divisions near the dovetail surface correspond to those of each 3D specimen model used in section 3.3.1. Fig.15 shows the details of the "shot-peened" model.

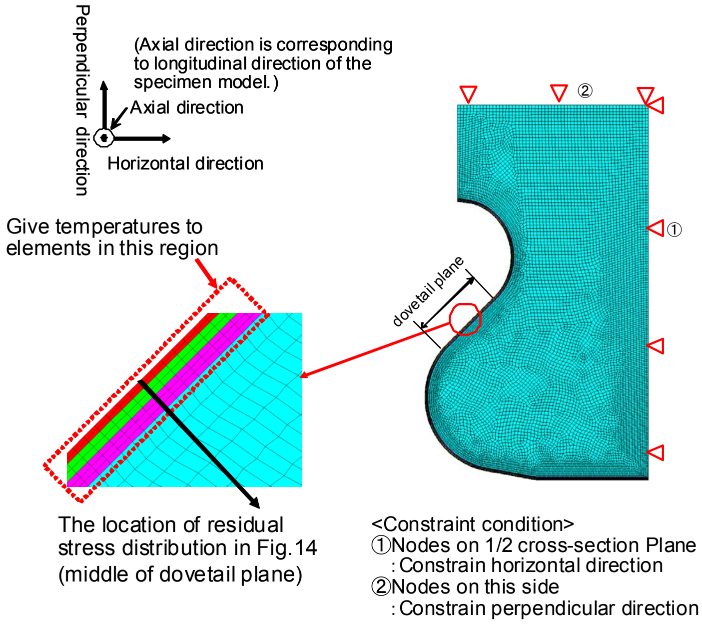


Fig.15 2D dovetail model (shot-peened)

3.4.2 Analytical procedure

The temperature distributions obtained in section 3.3 were assigned to the corresponding elements at the dovetail surfaces, and the residual stress distributions of the actual turbine blade dovetails were further obtained by conducting the elastic-plastic FE analyses.

3.4.3 Results

Fig.14 ("dovetail model") shows the residual stress distributions in the middle of the dovetail plane along the perpendicular direction to the plane for "shot-peened" ((a)), and "as machined" ((b)) condition along with the "specimen model" results described in section 3.3.3.

3.4.4 Discussion

For both the "shot-peened" and the "as machined" conditions, the residual stress distributions in the actual turbine blade dovetails are commonly characterized as follows, compared with those of the specimen models.

(1)The maximum compressive residual stress value for the actual dovetail is higher than the specimen model, and the compressive region is broader.

(2)The tensile residual stress region seems to be distributed throughout the dovetail thickness to balance the compressive residual stress region near the dovetail surface. As a result, the residual stress level in the tensile region is very low, which is significantly different from the simple "specimen model".

These are considered to be caused by the stiffness difference between the dovetail and the specimen.

4 CONCLUDING REMARKS

(1) A special method, combining the curvature method with the FE analysis, was adopted to estimate the residual stresses in the subsurface region of the turbine blade dovetail that are otherwise difficult to measure by the standard methods such as the X-ray diffraction method.

(2) Upon applying this method to the shot-peening specimen of wrought Alloy 718 material, the residual stress profiles of the specimen were obtained and compared to the results obtained using the X-ray diffraction method to verify its validity. The residual stress profiles obtained by both methods tend to be in good agreement and the quantitative differences in the maximum compressive stresses were considered to be reasonable upon taking into account the measurement errors etc. in both X-ray diffraction method and the present method.

(3) Stress values measured after each material removal step using the X-ray diffraction method are different from the original residual stresses along the thickness direction in the initial condition (before applying the electrochemical removal process). The present method enables an estimate of the stress distribution by reconstructing the FE model of the whole specimen. Moreover, it allows an estimate of the stress distribution in the original product condition using the FE model of the whole dovetail, which is one of the significant advantages of this method.

(4) Upon applying the present method to actual turbine blade dovetails, the residual stress distributions for both "shot-peened" and "as machined (not shot-peened)" surface were obtained. The residual stresses at "as machined" surface were also compressive although their distribution was shallower and their magnitude was lower than that at the "shot-peened" surface.

(5) As for the residual stress distribution of actual turbine blade dovetails, the tensile residual stress region seems to be distributed throughout the dovetail thickness to balance the compressive residual stress region near the dovetail surface. As a result, the residual stress level in the tensile region is very low.

(6) If the residual stress distribution is considered to be anisotropic, it could be estimated by means of obtaining bi-directional strains measured using a biaxial strain gauge. In that case, upon considering the dovetail size, the biaxial strain gauge must be small enough for installation and the wirings must be skillfully installed.

Once the bi-directional strains are obtained, these data would be used to match the FE analysis results qualifying the thermal expansions for each layer which are different in two directions by applying material anisotropy, that is, directionally different coefficients of linear thermal expansion, and the bidirectional residual stresses would be obtained by FE analysis.

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