FATIGUE LIFE AND RESIDUAL STRESSES IN COLD ROLLED PROPELLER BLADES

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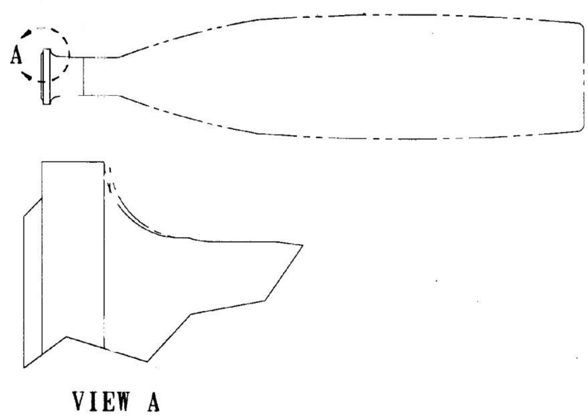
Abstract

This paper introduces a quantitative concept developed jointly by WR-ALC, the FAA, and the Technology for Energy Corporation to ensure the structural integrity of aluminum alloy propeller blades used on numerous military and civil aircraft. The propeller assembly of a turboprop engine is a highly energetic rotating assembly--that a catastrophic, single point failure in a propeller blade can cause catastrophic loss of aircraft is cause to question its structural integrity. To provide a useful fatigue life, the critical blade retention region is cold rolled to introduce residual compressive stresses in the surface of the appropriate magnitude and depth. Blind hole drilling has been employed for process verification, but this technique is qualitative in nature and is typically unsuitable for structures with stress gradients, such as those resulting from rolling. This tendency obviates the effectiveness of blind hole drilling as a quality control tool. In fact, there have been military and civil mishaps caused by premature blade failures attributed to inadequate rolling. Furthermore, the beneficial residual compressive surface stresses are degraded in service by wear, stress relaxation, and other damage that render the blades unserviceable. WR-ALC, the propeller repair center for all USAF aircraft, developed a rolling capability as part of the propeller overhaul process to re-introduce the effective compressive surface layer. Process parameters were optimized by x-ray diffraction residual stress measurement to quantitatively determine the resultant residual stress profile and avoid suspect tendencies of the blind hole drilling method, and a damage tolerance approach involving finite element modeling was specifically developed for the subject blades to ensure their structural integrity. This concept requires superimposition of the residual stress profiles with representative operational stresses in a finite element model. This approach predicted a near-infinite fatigue life for the rolled blades and confirmed the efficiency of the rolling process. The validity of the concept was demonstrated by correlation with baseline behavior of blades that were cold rolled by the original equipment manufacturer and which displayed acceptable service lives. While this concept was introduced to ensure the structural integrity of propeller blades, it is appropriate for a multitude other aircraft applications. These include rotating jet engine components such as fan, compressor, and turbine blades; hubs and gears; and aircraft structural members, such as shot peened wing skins, expanded fastener holes; and landing gear.

Introduction

The propeller assembly of a turboprop engine is a highly energetic rotating assembly. The propeller blades operate under severe load conditions during service which result in dominant bending loads that are imposed upon the blade at its inboard retention feature (Figure 1). To ensure the structural integrity of the blade and to provide a useful fatigue life, the critical blade retention region is cold rolled during manufacture by the OEM to introduce plastic deformation and residual compressive stresses in the surface of the appropriate magnitude and depth.

Figure 1. Blade retention feature



As a result of service, the blade retention region is routinely damaged by wear, corrosion, stress relaxation, and mechanical damage. This damage, which is repaired during overhaul, may exceed minimum service limits. In those cases, rerolling is required. In either case, i.e., during manufacture or overhaul, cold rolling is required to impart the required fatigue resistance to ensure the structural integrity of the blade.

The efficacy of the cold rolling process is verified by employing blind hole drilling techniques (BHD) to measure strain release rates. This technique is qualitative in nature and is intended specifically for measuring uniform residual strain states. However, this technique is typically unsuitable for structures with strain gradients, such as those resulting from the cold rolling process. Therefore, this tendency obviates the effectiveness of blind hole drilling as a verification technique in this application. Even though this technique has been adopted as the industry standard, empirical variation from the accepted specification (ASTM E837) is typically required because of this and other limiting tendencies.

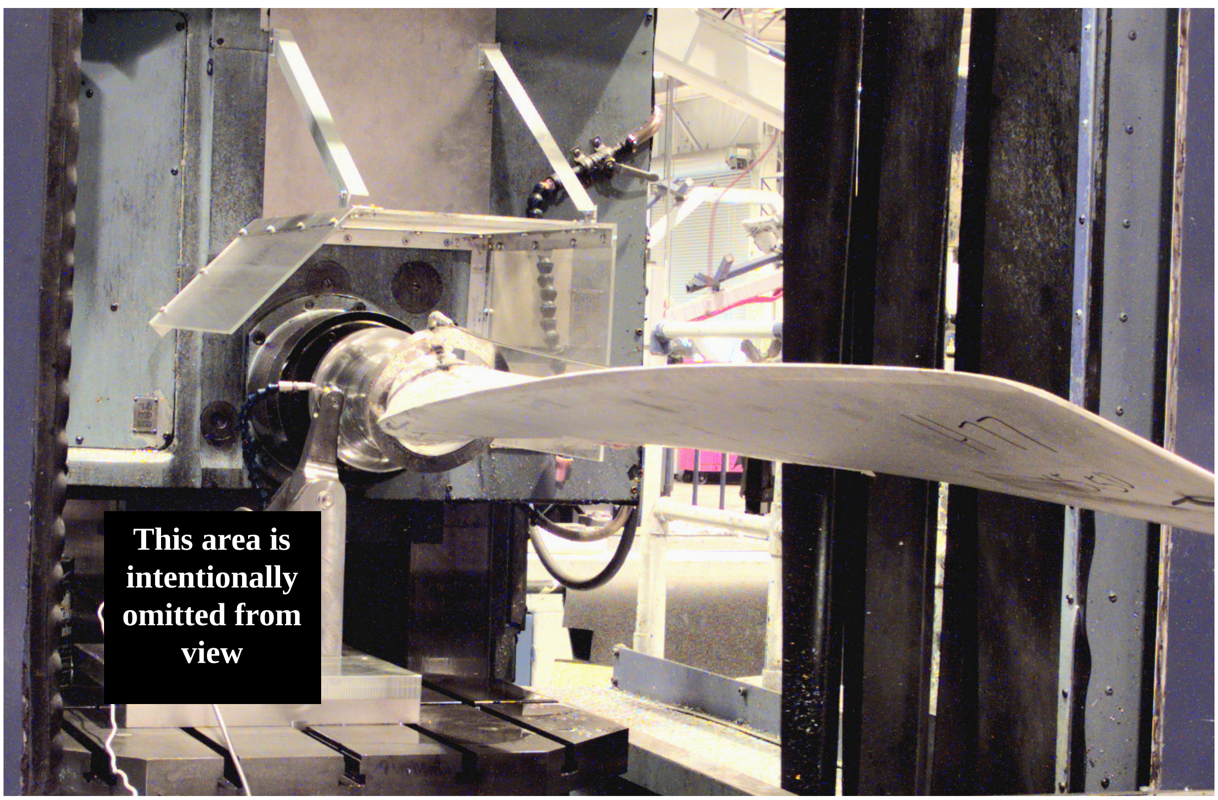
In acknowledgement of these tendencies, another approach, one more quantitative in nature, was devised. This approach was employed in conjunction with the development of an organic cold rolling process at WR-ALC, the USAF propeller repair center.

In this approach, the cold rolling process parameters were optimized by x-ray diffraction (XRD) residual stress measurement to quantitatively determine 1) the resultant residual stress profile and avoid the suspect tendencies of the blind hole drilling method, and 2) the depth of the cold work-induced plasticity. The residual stress levels and plasticity were incorporated into a nonlinear finite element model (FEM), and finally, damage tolerance analysis (DTA) was employed to ensure the structural integrity of the rerolled propeller blades.

Description of the Cold Rolling Process

Cold rolling, alternatively described as roller burnishing, employs a hardened, polished roller which is held in contact with the surface of the propeller blade, under load, while the blade is rotated. Proper cold rolling results in plastic deformation of the surface and the desired beneficial residual compression stress state. The relationship between rotational speed and tool feed rates, i.e., the load, and resultant residual stress is linear up to the point that the surface is damaged by excessive force. The roller, which is gently radiused, travels in the axial direction, with respect to the blade, resulting in the desired anisotropic behavior—the deformation, and therefore the residual stresses, are maximized in the axial direction to compensate for the predominant load case that results in blade deflection and bending loads in the retention area of the shank. The rolling process is conducted on a CNC Machining Center under the control of the appropriate program. Figure 2 shows a C-130 propeller blade prepared for the rolling process.

Figure 2. Rolling process



Description of the Analytical Approach

The development of this analytical approach was conducted according to the following procedure:

1. The residual strain profiles of blades representing the following conditions were measured by blind hole drilling:
    a. Strain-free baseline condition
    b. Cold rolled
        1. Organic rerolling process
        2. OEM rolled blades removed from service
2. The residual stress profiles of blades representing the following conditions were measured by X-ray diffraction:
    a. Strain-free baseline condition
    b. Cold rolled
        1. Organic rerolling process
        2. OEM rolled blades removed from service
3. The analytical approach was validated by:
    a. Correlation of organic and OEM products
    b. Correlation of techniques
4. The structural integrity of the rerolled propeller blades was evaluated by:
    a. Finite element modeling of the critical blade retention region
    b. Superimposition of residual and applied service stresses
    c. Fatigue crack growth analysis

The propeller blades that were the subject of this analytical process are described in Table 1.

Table 1. Description of propeller blade assets.

Description	**Sample Identification**	**Serial Number**
Stress relieved	N/A	876480
Organically rerolled	Re-rolled 1	821662
Organically rerolled	Re-rolled 2	794605
OEM-rolled and removed from service	Service 1	801495
OEM-rolled and removed from service	Service 2	781178
OEM-rolled and removed from service	Service 3	796551

Description of the Blind Hole Drilling Technique

Hole drilling and x-ray diffraction are the most commonly used methods for residual stress measurement. The former method, while more labor intensive, is the most widely used because the instrumentation and equipment are less expensive. The procedure has been standardized in ASTM E837, Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gage Method, for measuring residual strains that are essentially uniform with respect to depth.

According to the specification, a three-element strain gage (rosette) is adhesively bonded to the surface where the residual stress measurements are to be made; the strain gage elements are arranged around the circumference of a circle. The strain gage is connected to the appropriate instrumentation, and a small hole, with a diameter of D_0, is incrementally drilled in the geometric center of the rosette to specified depths using specific tooling. The strain gage circle diameter (D) is either 0.101, 0.202, and 0.404 inch, respectively intended for use with holes with nominal D_0 of 0.03125, 0.0625, and 0.125 inch. To provide flexibility, the specification allows variations in hole diameter, provided that $0.3 < D_o / D < 0.5$. Figure 3 shows the schematic arrangements of the strain gage elements, which are numbered 1, 2 and 3; these elements, respectively, measure the strains ε_1, ε_2 and ε_3. Strain gage element number 1 is used as a reference for measuring certain angles used in the computations; for simplicity, these angles are not shown or used here. For materials thicker than 4 D_o, as is the case fin this application, the drilled hole is blind and its maximum depth is 0.4 D; for thinner gage materials, the hole may be drilled completely through the thickness. The strain gage circle diameter (D) is marked on the rosette and a drilling guide is used as a depth indicator to monitor and record hole depth throughout the drilling operation.

The relieved strains (ε_1, ε_2, $_{\text{and}}$ ε_3) are measured by the rosette's elements and the instrumentation at the incremental depths, as the hole is being drilled. The minimum and maximum principle residual stresses, which are only measured at the bottom of each incrementally hole, are then mathematically derived for the biaxial stress state from the equation:

$\sigma_{min}, \sigma_{max} = (\varepsilon_3 + \varepsilon_1)/ 4A \pm \{ (\varepsilon_3-\varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1-2 \varepsilon_2)^2\}^{1/2} /4 B$ ....Equation 1

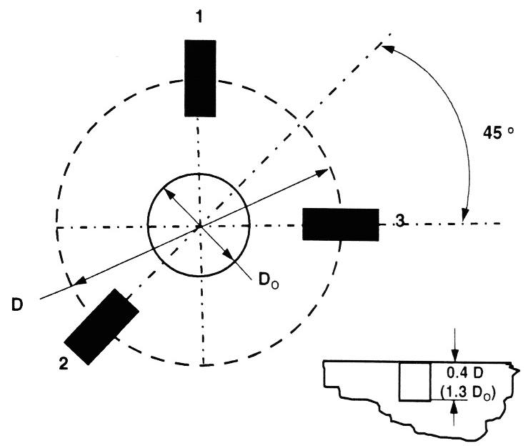
The relieved strains ε1, ε2, and ε3 are obtained from the maximum incremental depth. The empirical factors A and B are constants defined by:

$A = - \{(1 + \mu)/ 2 E\} a$ ....Equation 2

$B = - (1/ 2 E) b$ ....Equation 3

In equations 2 and 3, E is Young's modulus, μ is Poisson's ratio, and a and b are are dimensionless, material independent coefficients. For aluminum alloys, E and μ are $10.3X10^6$ psi and 0.33, respectively. The coefficients a and b, which depend on the ratio D_0/D, were derived from finite element analysis and are listed in Table 2 of the ASTM specification for D_O/D ratios in the 0.3-0.5 range. The coefficients a and b are 0.118 and 0.305 respectively (from ASTM E837, table 2). The corresponding A and B values are $0.0078X10^{-6}$ and $0.0153X10^{-6}$, respectively.

Figure 3. Rosette strain gage schematic



It is important to note that the hole diameter must accurate. This value is used, in conjunction with the strain gage circle diameter, to arrive at the appropriate D_0 / D ratio. This ratio is then used to determine the values of the a and b coefficients which, in turn, are used to compute the A and B constants.

Note in Equation 1, that the negative square root term is associated with σ_{max} because the empirical constants A and B have negative numerical values. Therefore, a tensile (+) residual stress will produce a compressive (–) relieved strain, and vice versa. Also note that accept/reject criteria are based on the stresses computed at the bottom of the hole. However, the ASTM specification does not describe any criteria—they must be specified. When specifying accept/ reject criteria, the required hole size must also be specified. This is because computed stresses depend on hole depth, which, in turn, is a function of hole diameter D_O. In general, larger holes are preferred because of the increased sensitivity. Smaller holes, on the other hand, are typically more suitable for small areas or where curved surfaces with small radii of curvature are involved.

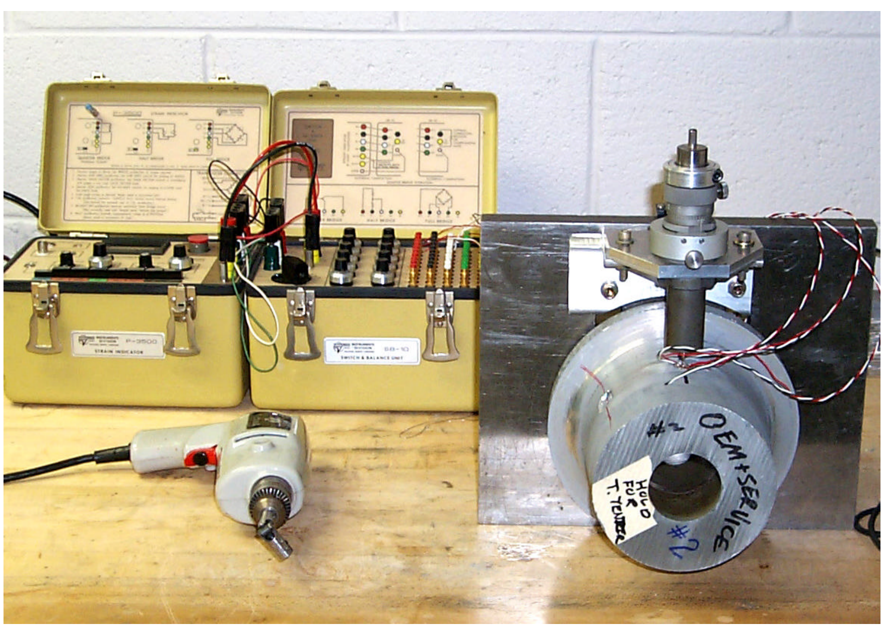
According to the ASTM specification, inaccurate computed stress values result from nonuniform residual stress/strain distributions. However, the specification prescribes a procedure used to test for uniformity. Certain strain functions ($\varepsilon_1 + \varepsilon_3$, $\varepsilon_3 - \varepsilon_1$ and $\varepsilon_1 + \varepsilon_3 - 2\ \varepsilon_2$) are monitored during the incremental drilling and plotted as functions of depth. If the shape of the resulting curve does not match a certain form, depicted in the specification, this is an indication of a nonuniform residual stress distribution and, therefore, hole drilling is not a valid method for determining those stresses. If, on the other hand, the shape of the resulting curve matches that of the depicted curve, hole drilling may be a valid method; i.e., matching the depicted form is no guarantee that a uniform stress distribution exists or that hole drilling is a valid method for the application.

The hole drilling technique, however, is characterized by significant limitations. The ASTM method is based on the assumptions that the residual stresses are uniformly distributed through the depth and that the computed stresses are less than 50% of the yield strength of the material—it is unlikely that a uniform stress distribution would result from a surface cold rolling operation, especially in this case where the diameter of the roller is small with respect to that of the workpiece, and if cold working results in plasticity, the stresses must have exceed the yield strength. Due to the complexity of the strain state and resultant biaxial solution, computation of stress from the measured relieved strains employs empirical constants typically predicated upon historical experience. Because there is no standard practice for resolving strain release rate inefficiencies in a stress strain gradient with this technique, there is no real correlation of blind hole drilling results since the industry employs different empirical approaches which typically lead to variability in derived residual stress levels. Furthermore, the uniformity test, prescribed as part of the ASTM specification, does not guarantee that residual stress distribution is uniform. Apart from this, the actual depth of the cold worked layer is not, in any way, related to the depth of the drilled hole. Moreover, the computed stress, i.e., σ_{min} or σ_{max}, at the bottom of the hole (or at any other depth) does not represent the actual residual stresses at that location. Rather, it represents an equivalent uniform stress, or average stress from the surface to the bottom of the hole (or increment), which would produce the same relieved strain.

Unfortunately, the limitations described above cast some doubt upon the hole drilling technique as a quality control tool to assess the effectiveness of the propeller blade rolling operation.

The experimental blind hole drilling configuration is shown in Figure 4.

Figure 4. Blind hole drilling instrumentation.



Description of the X-ray Diffraction Technique

X-ray diffraction is a non-destructive, residual stress analysis technique that measures the surface strain in the crystal lattice, i.e., the distance between sets of known parallel atomic planes. This technique is applicable for crystalline materials that are fine-grained with random grain orientation. In this case, the large propeller blade forgings meet this requirement.

Residual stresses are only those stresses that exist in the absence of external loads, and by definition, these residual stresses represent only the elastic strains. It should be understood that strains in excess of the elastic limit, results in plasticity and attendant effects such dislocation transportation, lattice distortion, etc. with no appreciable increase in the measurable macro-scale strains. In other words, any residual stress remaining after the onset of plasticity must be elastic.

This technique involves imparting a single wavelength x-ray beam onto the location of interest at several tilt angles. The interaction between the x-ray beam and the atomic planes of interest creates a diffraction peak at a specific angle. The location of the diffraction peak is used to calculate the lattice parameter, i.e., the distance between the atomic planes, d. By analyzing the diffraction peak location at each tilt angle, the residual strain can be derived by measuring the peak shift.

The residual stress is calculated by multiplying the strain by the x-ray elastic constant according to:

$\sigma_\phi = \Delta d/d_o / (½ S_2 \sin^2\psi)$ …………………………………..…………...Equation 4

In Equation 4, σ_ϕ is the stress in the direction of the x-ray beam tilt angle, $\Delta d/d_o$ is the change in atomic spacing divided by the unstressed atomic spacing, i.e., strain, ψ is the relative x-ray beam tilt angle, where:

$½ S_2 = (1 + \nu) / E$ (the x-ray elastic constant) ....Equation 5

When x-ray diffraction is employed to determine residual stresses at various depths, surface material is removed via electrochemical polishing without imparting a change in the existing residual stress state, and specific corrections are made for stress gradients to account for superficial beam penetration and strain relaxation due to material removal. These corrections are defined and prescribed per SAE J784a.

X-ray diffraction allows for non-destructive surface measurements on large components. It is a direct measurement of strain that does not require a calibration specimen. The process is fast (less than 10 minutes) and repeatable. Unlike BHD, the technique is appropriate for measuring complex geometries, and perhaps most importantly, applicable standards and practices do not limit the x-ray diffraction technique when high stress gradients through the depth exist.

The x-ray diffraction concept and experimental configuration are shown in Figures 5 and 6 respectively.

Figure 5. X-ray diffraction concept.

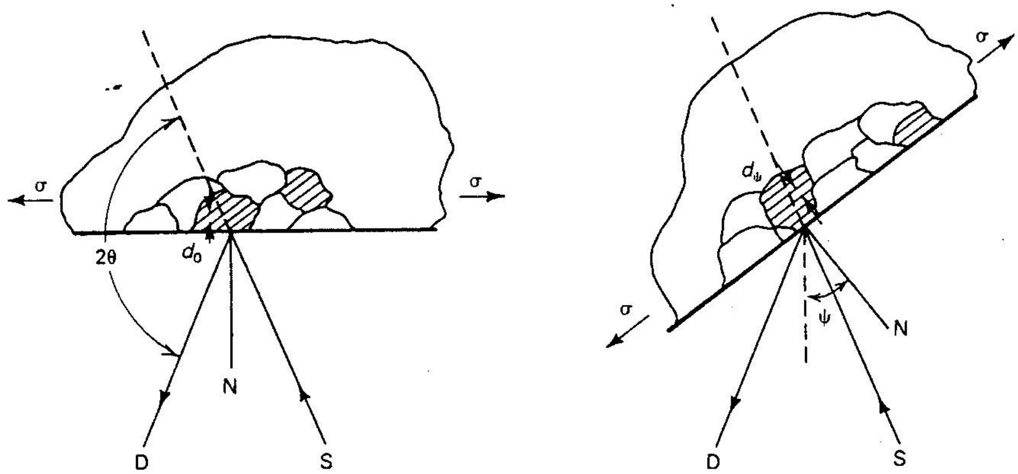


Figure 6. X-ray diffraction instrumentation.

Furthermore, the diffraction peak width is a measure of plastic strain. In this application, the peak width was measured as the full width at half the maximum intensity (FWHM). This paper utilizes FWHM as a qualitative measurement of plastic strain. Since the diffraction peak width broadens or widens due to plasticity, FWHM is proportional to plastic strain.

Since the cold rolling process also results in a surface plasticity, the relationship between FWHM and depth, coupled with residual stress analysis, is an important indicator of effective depth of the cold rolling process.

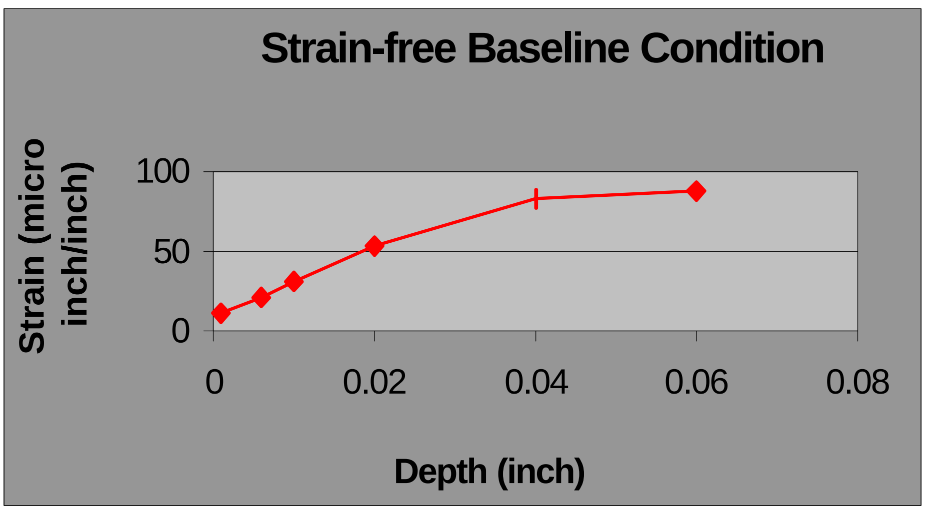
Results

Determination of Residual Strain Profiles by Blind Hole Drilling

Blind hole drilling was performed according to Measurements Group, Inc. Tech Note 503-5, Measurement of Residual Stresses by the Hole-Drilling Strain Gage Method, and ASTM Standard Test Method E837. Micro-Measurements Group EA-13-062RE-120 precision rosette strain gages, were adhesively bonded to the surface with M-bond 200 adhesive. A hole of 0.0625 inch diameter was drilled incrementally using an RS-200 precision milling guide. The strain gage output was connected by a Vishay Measurements Group SB-10 Switch and Balance Unit and was processed by a Vishay Measurements Group P-3500 Strain Indicator.

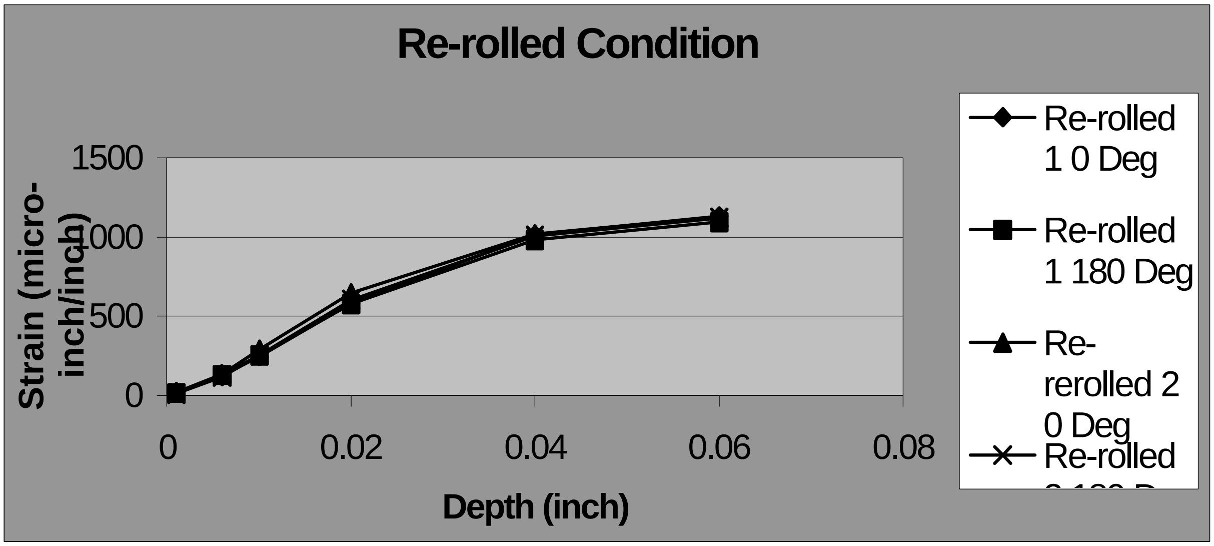
The strain-free baseline condition was represented by a propeller sample that was heat treated at 300 degrees F for 2-hours followed by machining to remove 0.080 inch, as measured diametrically, by turning on a lathe. Blind hole drilling of this baseline element confirmed that the thermal stress relieving in conjunction with surface machining reduced the residual strain levels to near neutral, as illustrated in Figure 7.

Figure 7. Strain release rates of strain-free baseline condition



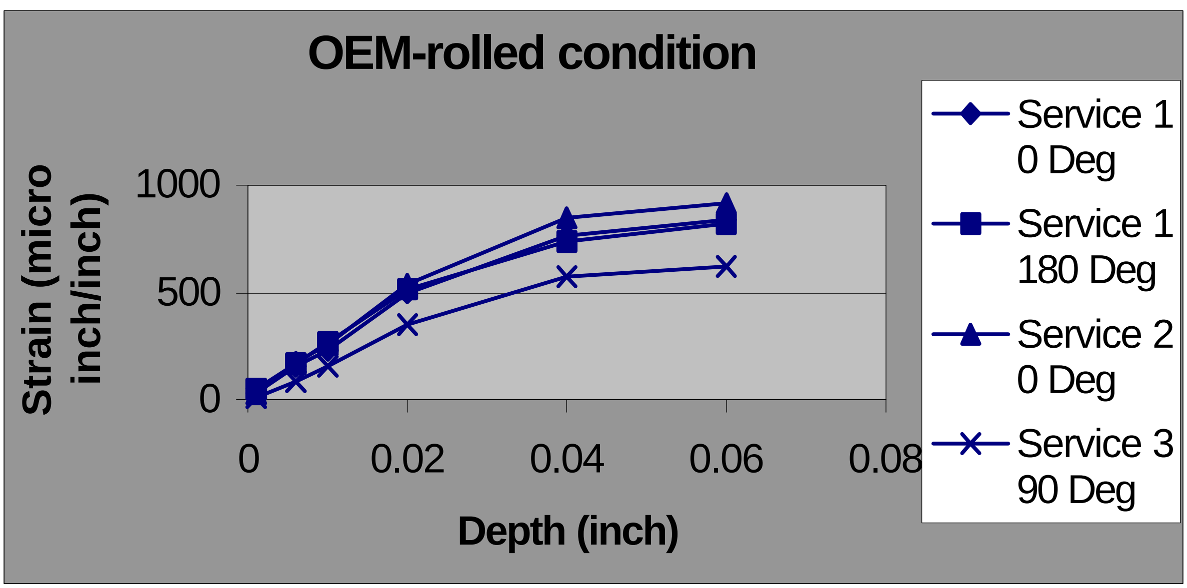
After cold rolling in accordance with the organic process specification, the strain release rate was measured by blind hole drilling. The strain release rates of two cold rolled propeller blade samples, each measured at the 0 and 180 degree positions, are illustrated in Figure 8.

Figure 8. Strain release rates after cold rolling, as measured in the shank



To confirm the validity of this analytical concept, correlation with behavior of blades that were cold rolled by the original equipment manufacturer, and which subsequently displayed acceptable service lives, was required. Therefore, several blades were removed from service for blind hole drilling. The results from this control group are shown in Figure 9.

Figure 9. Strain release rates in the control group of OEM-rolled blades removed from service.

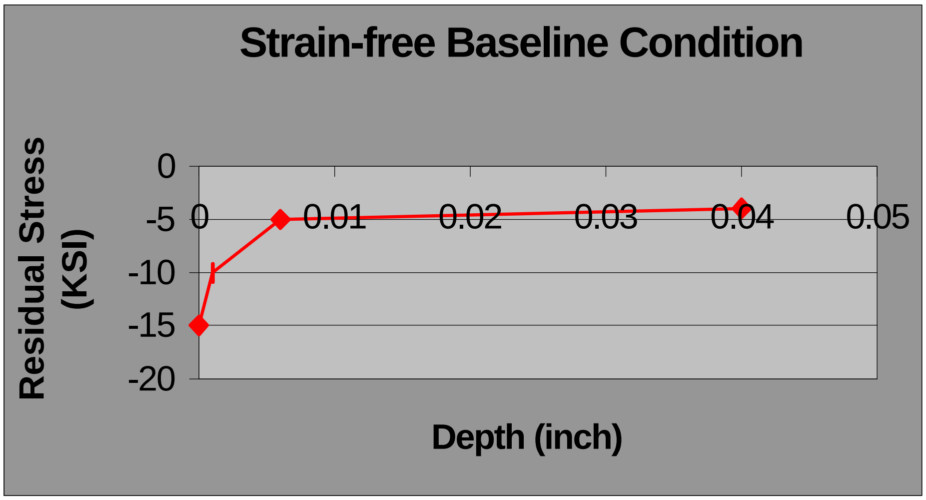


Determination of Residual Stress Profiles by X-ray Diffraction

The residual stress states were determined by Technology for Energy Corporation (TEC) in Knoxville, TN via x-ray diffraction (XRD). A TEC model diffractometer, using a copper (K α) target at 45 kV and 1.5 mA was employed to excite the crystallographic planes of interest [333]; the diffraction angle (2θ) was 162 degrees. The diffractometer and the propeller blades were oriented to determine residual stresses in the axial or predominant load direction, and a rectangular collimator of 1mm x 5 mm size was used.

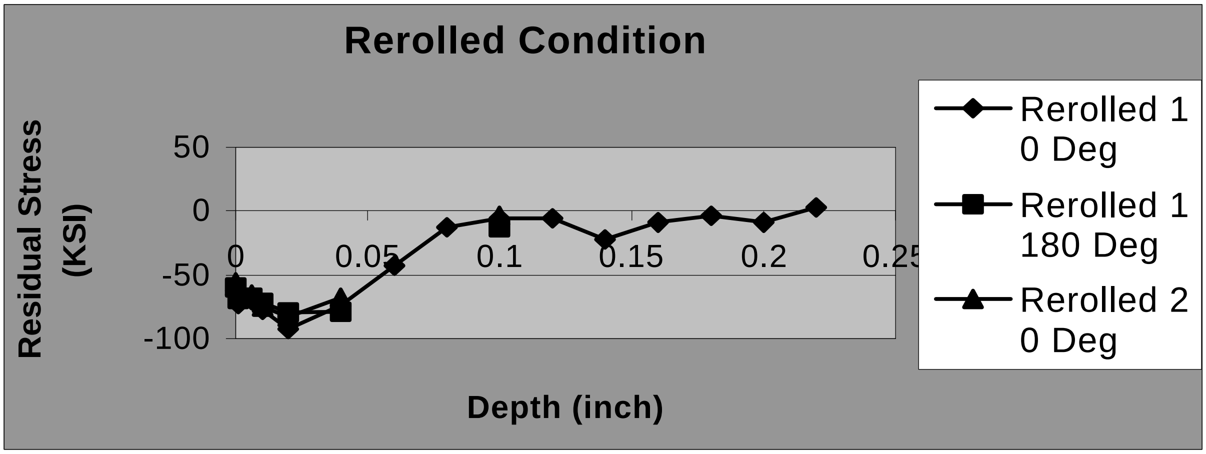
The residual stress measurements of the strain-free baseline element confirmed that this sample was indeed neutral with respect to residual stress levels, Figure 10.

Figure 10. Residual stress profile in strain-free baseline propeller blade sample.



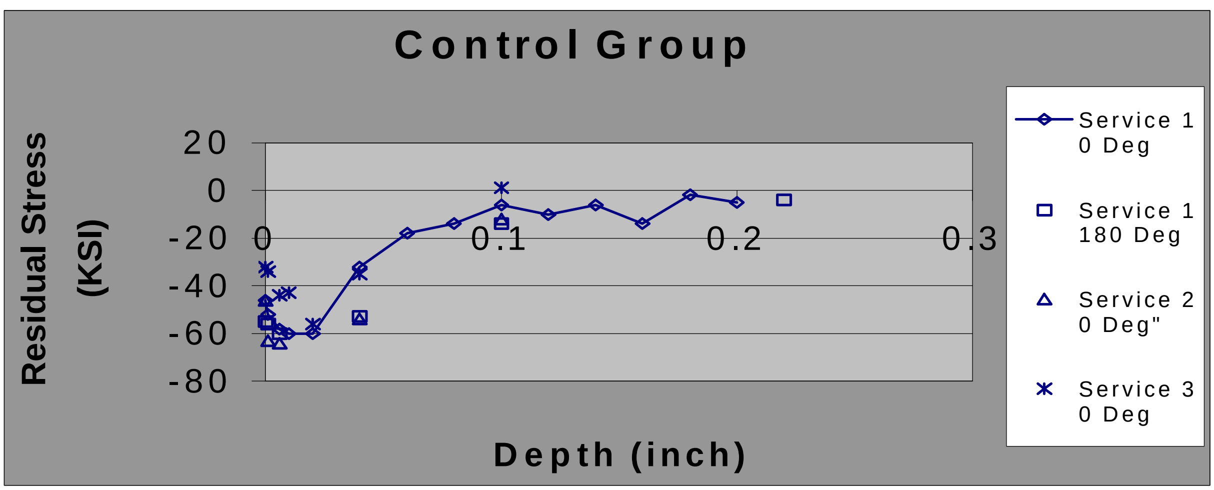
After cold rolling in accordance with the organic process specification, the residual stress profile was measured by blind hole drilling. The strain release rates of two cold rolled propeller blade samples, are illustrated in Figure 11. Note that the residual stress profile was determined at both the 0 and 180 degree positions for only one sample.

Figure 11. Residual stress levels after cold rolling, as measured in the shank.



The residual stress profiles of the control group of OEM-rolled service blades were also determined, see Figure 12.

Figure 12. Residual stress profiles of the control group

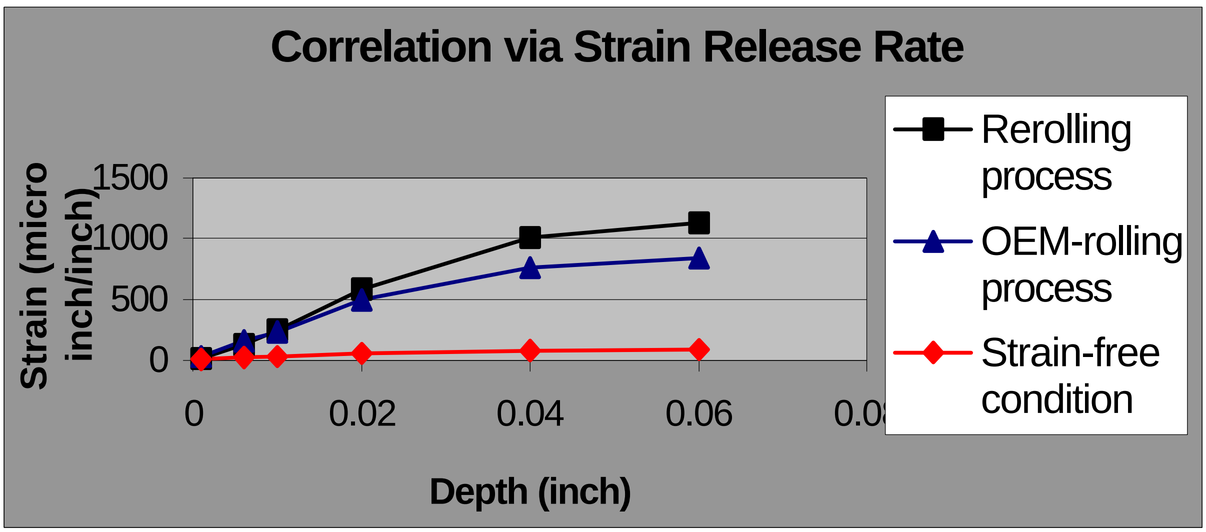


Correlation

In order to determine the validity of both the rolling process and this analytical approach, correlation with the behavior of the control set, i.e., the blades that were cold rolled by the original equipment manufacturer and which displayed acceptable service lives, was required.

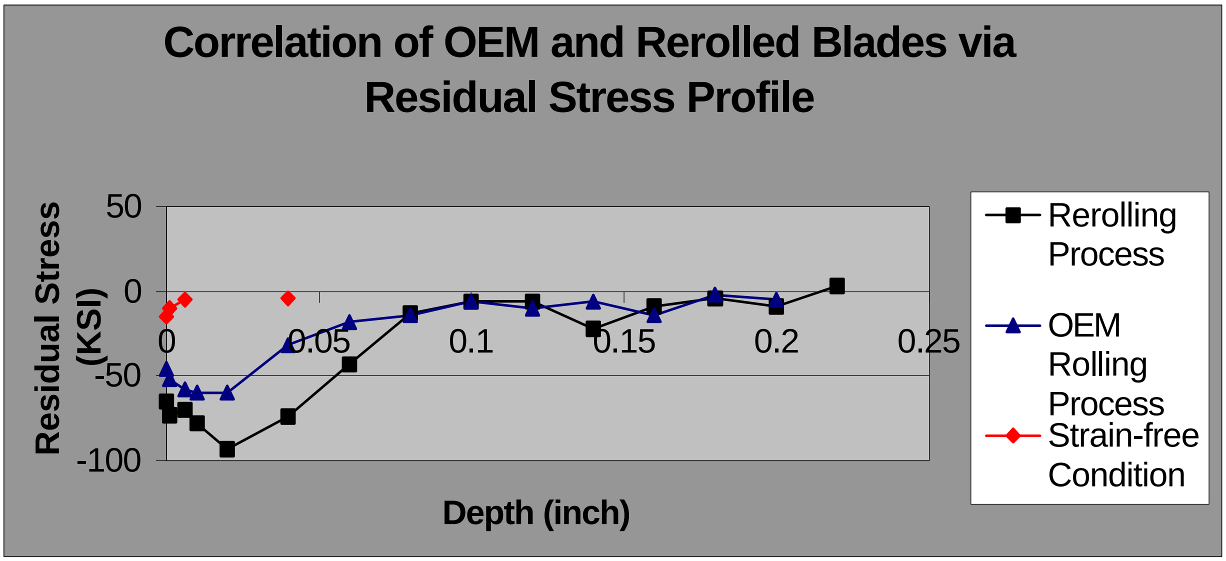
The behavior of the rerolled blades showed acceptable correlation with the behavior of the OEM rolling process by the accepted blind hole drilling technique, see Figure 13. This validated, by correlation, the efficacy of the organic rolling process based on the accepted blind hole drilling technique. Please note that that the results attributed to the OEM rolling rolling process were attained from propeller blades that were removed from service—the effects of stress relaxation and any previous repair or overhaul process may not have been accounted for. Nevertheless, the organic rolling process results in slightly higher strain release rates than that displayed by blades removed from service.

Figure 13. Comparison of strain release rates resulting from organic rerolling and OEM rolling.



Similarly, the behavior of the rerolled blades also showed acceptable correlation with the behavior of the OEM rolling process by the x-ray diffraction technique, see Figure 14. This validated, by correlation, the efficacy of the organic rolling process based on the x-ray diffraction technique. Please note that that the results attributed to the OEM rolling rolling process were attained from propeller blades that were removed from service—any effects attributed to stress relaxation or previous repair or overhaul processes may not have been accounted for. Nevertheless, the organic rolling process clearly results in residual stress profiles that are slightly more compressive than that displayed by blades removed from service.

Figure 14. Comparison of residual stress profiles resulting from organic rerolling and OEM rolling.



X-ray diffraction results in quantifiable data based upon a material constant, the lattice parameter "d", and a measurable material property, i.e., the change in the lattice parameter due to strain. On the other hand, blind hole drilling yields a strain solution based upon a physical reaction and an empirical solution to a complex problem. However, even in acknowledgement of the limitations of the strain release rate solution, yet another empirical method can be applied to strain release rates in a strain gradient via an equivalent uniform stress, as described previously. In this particular case, equivalent uniform stresses were derived from the strain release rates via the ReStress program. This allows correlation of residual stress measurement by x-ray diffraction and strain release rate measurement. X-ray diffraction data and the computed equivalent uniform stresses are shown in Figures 15, 16, and 17 in the strain-free, rerolled and OEM-rolled cases, respectively.

Figure 15. Correlation of principle residual stresses by x-ray diffraction and equivalent uniforn stresses by Restress in the strain-free case.

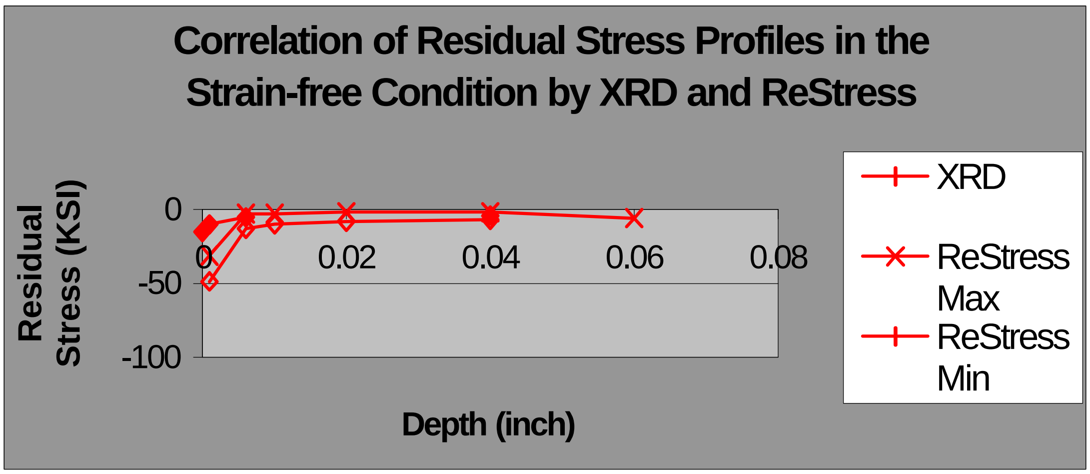


Figure 16. Correlation of principle residual stresses by x-ray diffraction and equivalent uniform stresses by Restress in the rerolled case.

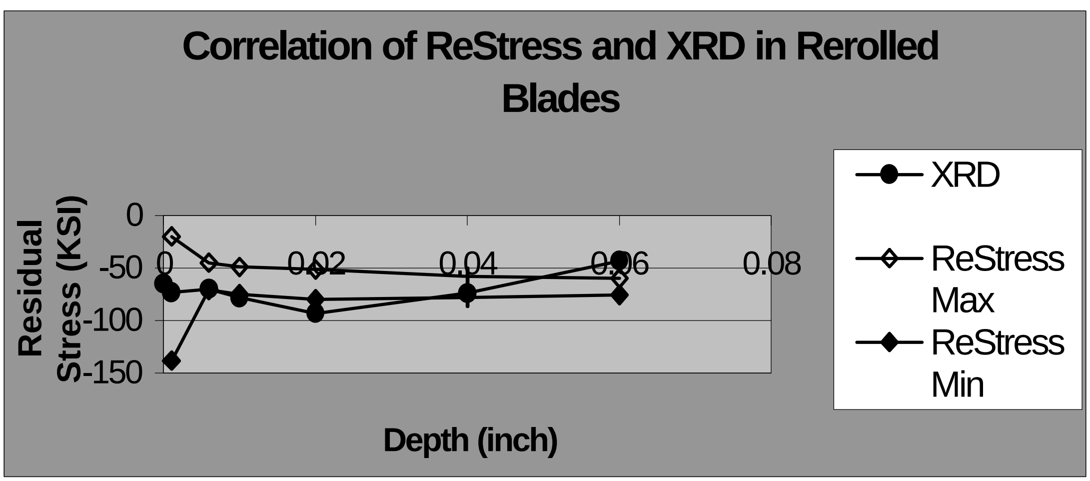
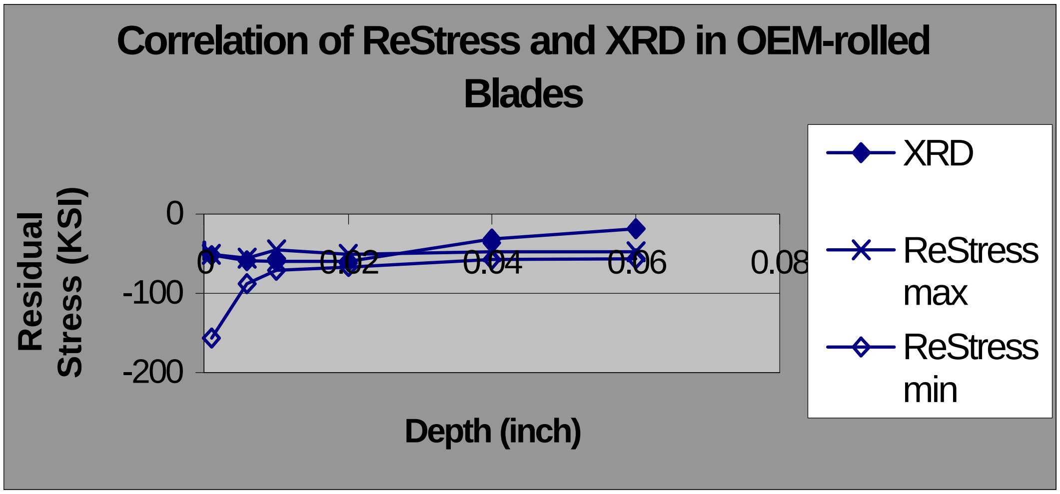


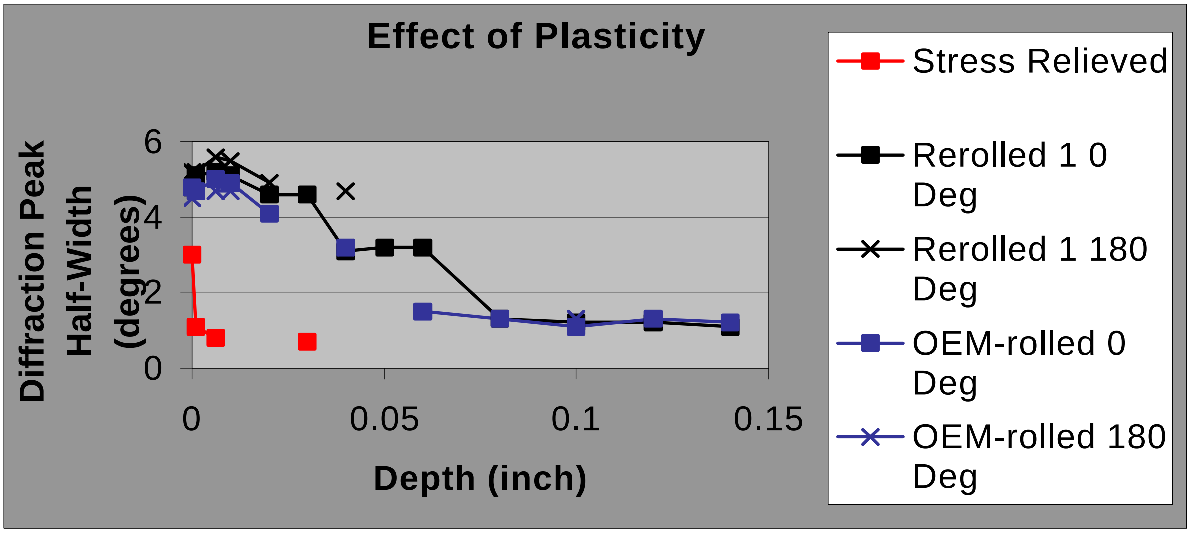
Figure 17. Correlation of principle residual stresses by x-ray diffraction and equivalent uniforn stresses by Restress in the OEM-rolled case.



Analysis of this data confirms the errors associated with blind hole drilling in the presence of a stress/strain gradient. Even in the strain-free case, the equivalent uniform stresses tend to be significantly less than indicated principle stresses. Furthermore, in the presence of severe stress/strain gradient, as in both the rerolled and OEM-rolled cases, the equivalent uniform stresses show nearly constant magnitude with depth beyond some nominal, but relatively shallow depth, i.e., the asymptotic transition, even though the principle residual stress profile must be becoming less compressive with greater depths. This deviation from classical behavior is further corroboration of the suspicions regarding this technique and may lead to significant non-conservatism, especially at depths of greater than 0.020 inch.

Furthermore, x-ray diffraction techniques allow quantification of the depth of rolling-induced plasticity by measuring the breadth or width of the diffraction peak. Since the diffraction peak width is proportional to plasticity, this measurement becomes an indicator of effective cold working depth. Therefore, by plotting peak half-width versus depth, the depth of plasticity can be determined. The observed cold working depth indicator of the rerolled and OEM-rolled conditions is shown in Figure 18. In general, the peak width was relatively large at or near the surface and asymptotically approached a minimum peak width at some depth beneath the surface. The depth at which the peak width approaches the minimum value indicates the effective depth of cold working. By correlating FWHM to residual stress levels, the FWHM drops off after the maximum subsurface compressive stresses are reached. However, the depth at which the minimum FWHM is approached may also be attributed to sample and/or process variations. When comparing the FWHM of the baseline, i.e., stress relieved coupon to both the OEM-rolled blades removed from service and the rerolled coupons, there is a significant difference in peak widths. The stress relieved sample has a moderate peak width at the surface (3 degrees) which drops off at 0.001” to approximately 1 degree. This 1 degree width represents a minimum value. The service and rerolled blades showed similar trends, thus indicating the effective cold work depth for those cases.

Figure 18. Depth of plasticity in rerolled and OEM-rolled conditions.

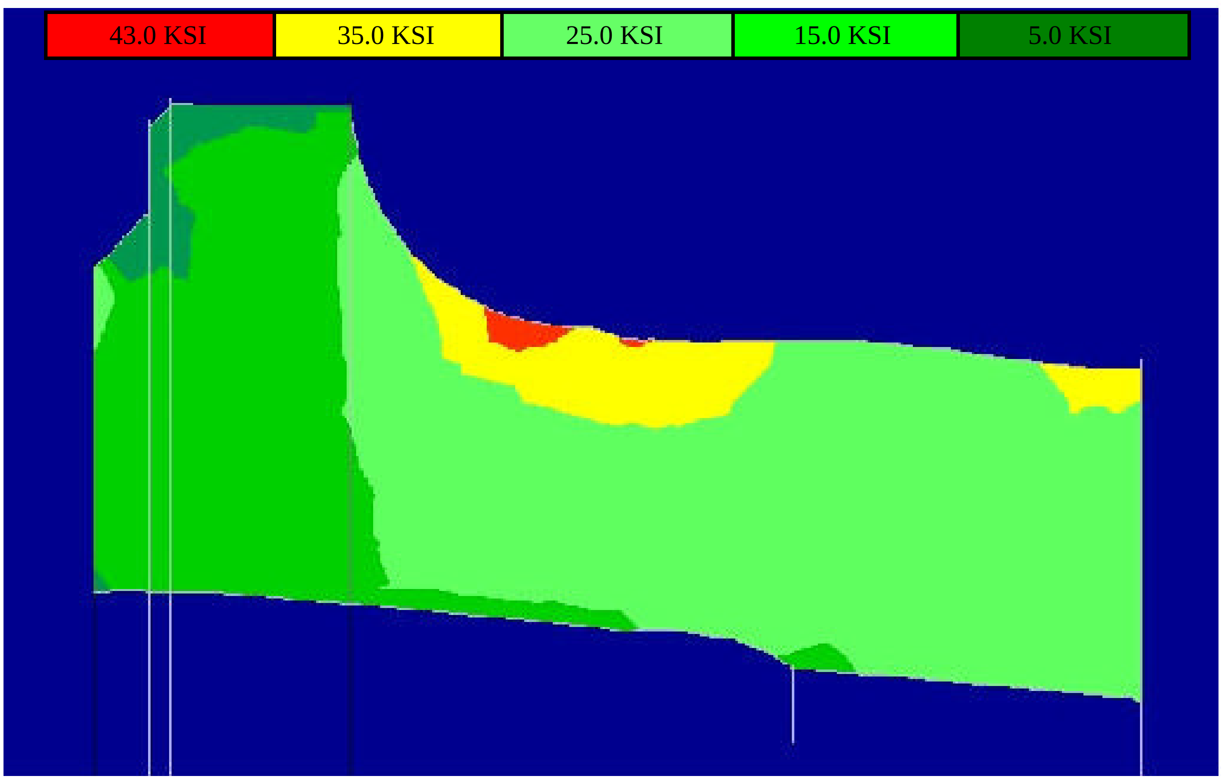


Finite Element Modeling and Non-linear Analysis

The structural integrity of a propeller blade is dictated by its fatigue life. Since maximum service loads are concentrated in the blade retention fillet, the fillet constrains the fatigue life of the blade. Therefore, the structural integrity methodology was focused primarily on the retention fillet. This methodology employed finite element modeling, and analysis by superimposition of residual and applied stresses.

Representative empirical and quantitative residual stress profiles were exported to a finite element model of a C-130 propeller blade, see Figure 19, which was constructed in Pro Engineer to determine the maximum stresses in the fillet under conditions of combined vibration and centripetal and aerodynamic loads, . The vibratory and centripetal loads are a direct function of the geometry, mass, pitch, and rotational velocity of the propeller blade. The aerodynamic loads were determined through the use of a strip model—by dividing the blade into elements.

Figure 19. Depiction of finite element model for maximum load case.

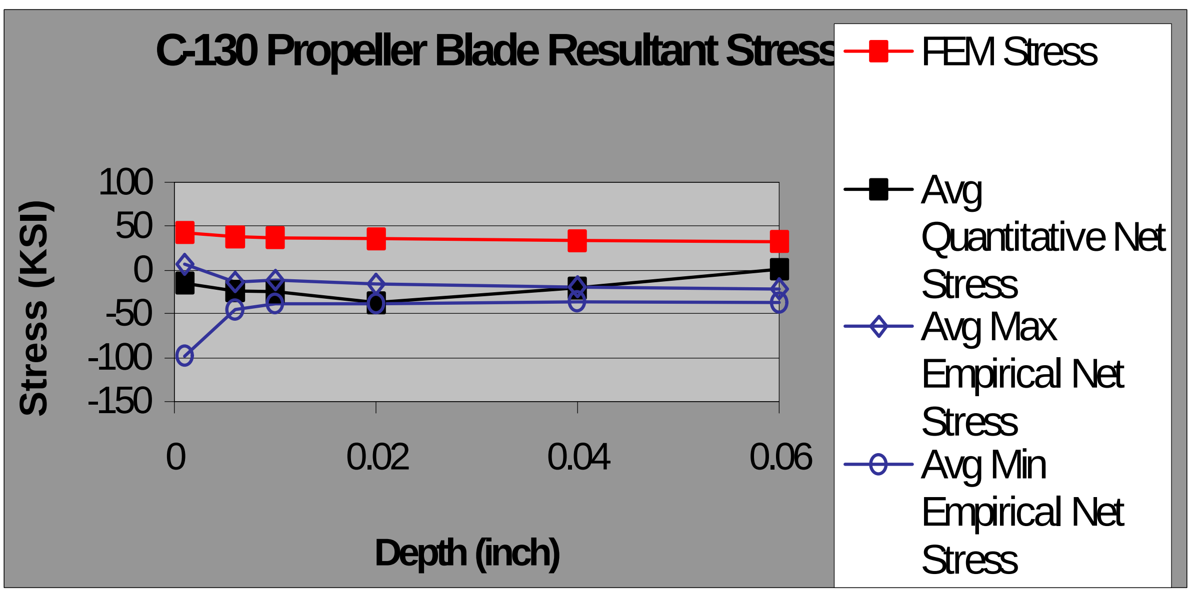


The model's stress profile and representative empirically and quantitatively derived residual stress profiles are depicted in Figure 20, along with the resultant fillet stresses (assuming that a linear relationship exists between imparted residual stresses and load induced stresses). Note that both the quantitative and empirical net stress profiles are averages derived from the rerolled and OEM-rolled blades removed from service.

Analysis of the residual and service stress profiles shows that under the modeled conditions, the fatigue life of an unrolled blade, based upon quantitatively derived residual stress, was found to be less than 10^5 cycles. On the other hand, the fatigue life of a rerolled blade, based upon quantitatively derived residual stress is greater than 10^8 cycles, i.e., near-infinite. This analysis is based upon the maximum take-off propeller blade load at sea-level, and S/N data published in MIL-HDBK-5.

Load spectrums have also been developed that represent worst case and best case models including the following operational profiles: take-off and landing, banks, low level, special operations, and ferry. These load spectrums were used by the OEM to estimate the number of cycles that a typical propeller blade would be exposed to for each phase of flight over a period of one year. This number was used in conjunction with the stress state applicable to each phase to determine that the analytical blade life for an unrolled propeller blade is between 400 flight hours for a AC-130U and 3,000 flight hours for a C-130 operated in a long-range airlift mission. The load spectrum of the AC-130 represents the worst possible case on the propeller blade, primarily because of the high gross weight of the aircraft special mission elements. The upper fatigue limit represented as the long-range airlift mission is representative of much of the C-130E, C-130H, and EC-130 missions with the exception of any low level operations. This analysis correlates well with observed behavior—actual catastrophic failures have occurred only on aircraft operated in long-range airlift missions, and these failures have occurred between 2,300 and 2,500 flight hours, roughly corresponding to the projected life for the unrolled condition.

Figure 20. Resultant stress profile.



Furthermore, a previous analysis by Jansen and Drury revealed that initiation life varies significantly with minor stress concentration effects. The conclusion suggests that the variability of cold working and notch sensitivity of the fillet on this propeller results in unreliable propeller life prediction if the retention fillet is not properly cold rolled. Further, cold working does not enhance fatigue life when a rogue flaw (0.125 inch) is assumed, per MIL-A-83444, because the flaw would extend through the maximum residual compressive stress.

Based on these analyses and experience, proper cold rolling of these propeller blades has the effect of providing near-infinite fatigue life providing there are no surface defects that extend beyond the area affected by cold rolling and that the maximum stress as determined by the FEM is not exceeded.

Conclusions

This joint effort by WR-ALC, the FAA, and TEC demonstrated the validity of a quantitative concept and confirmed the structural integrity of rerolled C-130 propeller blades.

Due to the severity of the service conditions, propeller blades are cold rolled during manufacture to induce surface plasticity and a beneficial residual compressive stress. In the absence of minimum compressive residual stress, the loads and the resultant stresses developed in the blade during service, culminate in catastrophic failure. Due to the effects of wear, corrosion, and maintenance practices, the blades are also rerolled to restore the beneficial residual surface stresses. This concept was intended to provide quantitative analysis of residual stresses induced in the critical blade retention region of propeller blades by cold rolling, specifically in a rerolling application, by x-ray diffraction—as opposed to the current empirical blind hole drilling techniques.

Residual stresses were determined in rerolled and OEM-rolled propeller blades via blind hole drilling and x-ray diffraction techniques. Blind hole drilling was performed in accordance with ASTM E837.

Blind hole drilling and X-ray diffraction techniques were correlated by comparison of experimental results. This correlation confirmed the empirical nature and inaccuracies of the blind hole drilling technique in applications characterized by stress/strain gradients.

The residual stress profiles, derived by blind hole drilling and x-ray diffraction, in the rerolled blades were correlated with OEM-rolled blades. This correlation, which was premised upon the acceptable performance of the OEM-rolled blades, confirmed that the organic rerolling process resulted in adequate residual stress levels and thus validated the analytical techniques.

This concept employed superimposition of the quantitatively derived residual stress profiles with representative operational profiles in a finite element model which predicted a near-infinite fatigue life, thus verifying that the quantitative concept ensures the structural integrity of the rerolled propeller blades.

This quantitative concept, which was introduced as an improved method to ensure the structural integrity of propeller blades, may be appropriate for a multitude of other similar applications which include other rotating jet engine components and aircraft structures that benefit from compressive surface enhancement techniques.

Further evaluation is ongoing with respect to other areas with the potential to improve this concept and rerolling processes. These include the application of meandering winding magnetometry (MWM) and further non-linear modeling and analysis using elastic-plastic theory.

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