





## WHAT IS RESIDUAL STRESS?

Residual stress is the internal stress distribution locked inside a material. These stresses are present even after all external loading forces have been removed. They are a result of the material obtaining equilibrium after it has undergone plastic deformation.

## HOW DOES RESIDUAL STRESS COMPARE TO APPLIED STRESS?

Applied stress is generated inside a material due to an external load (often measured with a strain gauge). Residual stress is present inside the material regardless of loading. The total stress experienced by the material at a given location within a component is equal to the residual stress plus the applied stress.

$$\text{TOTAL STRESS} = \text{RESIDUAL STRESS} + \text{APPLIED STRESS}$$

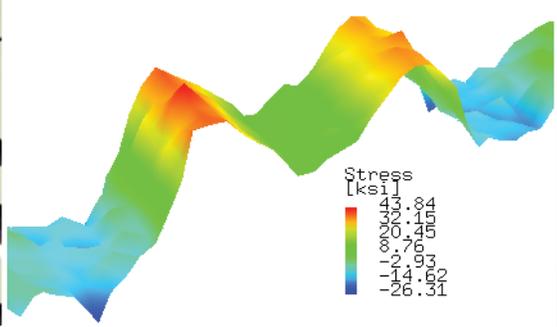
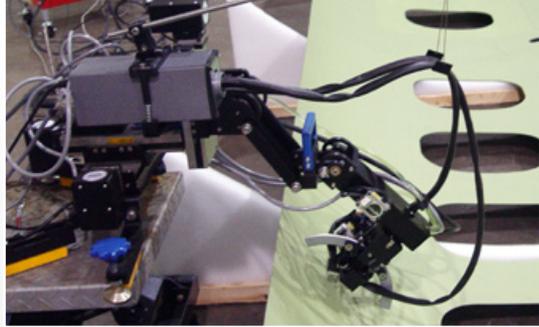
If a material with a residual stress of a -400 MPa is subjected to an applied load of +500 MPa. The total stress experienced by the material is the summation of the two stresses (+100 MPa). Therefore, knowledge of the residual stress distribution is important to determine the actual loads experienced by a component. In general, compressive residual stress in the surface of a component is beneficial. It tends to increase fatigue strength and fatigue life, slow crack propagation, and increase resistance to environmentally assisted cracking such as stress corrosion cracking and hydrogen induced cracking. Tensile residual stress in the surface of the component is generally undesirable as it has the opposite effect.

Compressive (-) residual stress acts by pushing the material together, while tensile (+) residual stress pulls the material apart, enabling small cracks to grow at a faster rate. Stresses are characterized as either a normal stress that acts perpendicular to the face of a material or a shear stress that acts parallel to the face of a material. There are a total of 6 independent stresses (3 normal and 3 shear) at any point inside a material.

## WHAT CAUSES RESIDUAL STRESS?

Residual stresses are generated, upon equilibrium of material, as a result of plastic deformation caused by applied mechanical loads, thermal loads or phase changes. Mechanical and thermal processes applied to a component during service can also alter its residual stresses.

MECHANICAL	Plastification of a material during machining.
THERMAL	Difference in solidification of the material. (i.e. in a cooling casting)
PHASE CHANGE	Precipitation / Phase transformation resulting in a volume change (i.e. Austenite to Martensite)



## RESIDUAL STRESS MEASUREMENT

### RESIDUAL STRESS MANAGEMENT

Harmful residual stress can lead to stress corrosion cracking, distortion, fatigue cracking, premature failures in components, and instances of over design. Techniques, such as heat treating, controlled cooling and localized heating are applied to help manage potentially harmful residual stresses created during manufacturing. Other techniques, such as shot peening, are used to introduce beneficial residual stress into a component to help increase fatigue life. Knowledge of the residual stresses is required to ensure that these processes have been correctly applied. Small changes in the residual stress can often have a significant effect on the life of a component.

### IMPORTANCE OF RESIDUAL STRESS

Residual stress affects:

- Low cycle and high cycle fatigue performance
- Distortion during machining and after applying a process
- Peen forming (controlled distortion)
- Fretting
- Stress corrosion cracking (SCC) and hydrogen initiated cracking (HIC)
- Crack initiation and propagation



### THE BENEFITS OF MEASURING AND MONITORING RESIDUAL STRESSES

- Optimize manufacturing processes
- Provide a quantitative metric to enable specifications and Go/No-Go decisions
- Improve product quality, substantiate supplier quality, engineering source approval (ESA)
- Improve safety and reduce catastrophic failures
- Extend component life by ensuring sufficient compressive residual stress is present
- Validate repair area has been "restored" to original specifications.
- Residual stress information can improve the probability of detection of other nondestructive techniques.
- Validate residual stress distribution from FE models or fracture mechanics



Some of the platforms that PROTO has worked on - photos courtesy of USAF and NASA

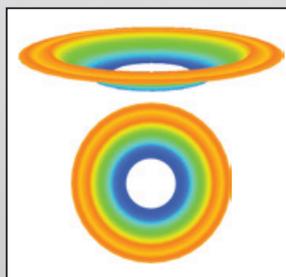
# AEROSPACE

## MEASURING RESIDUAL STRESS IN AEROSPACE STRUCTURES

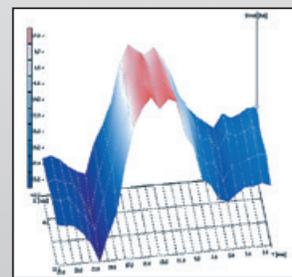
Residual stresses play a key role in the life of aerospace structures. PROTO provides both measurement services and x-ray diffraction residual stress measurement instrument sales, enabling our customers to obtain residual stress measurements in the lab or in the field on aerospace components such as:

- Skins • Wings • Frames
- Landing Gears • Engine Supports
- Engine Casings • Engine Cowlings

Some of the platforms PROTO has worked on include: C-141, B-2, Space Shuttle, Joint Strike Fighter, Boeing 777, Dash 7



Residual stress map of a cold expanded hole

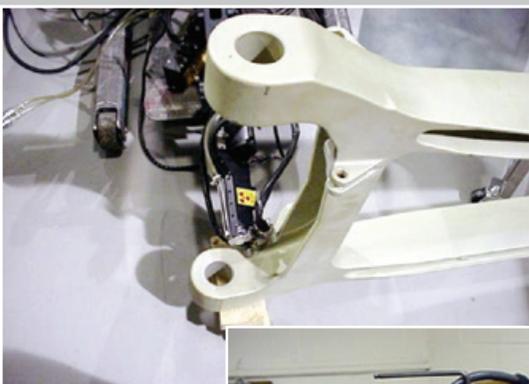


Residual stress map of a weld

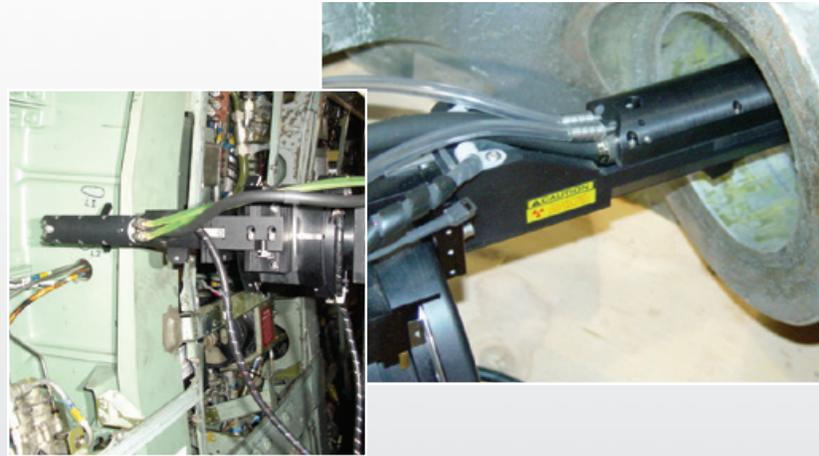
## PROBLEM SOLVING

Aerospace problems that can be addressed using PROTO Systems and Services include:

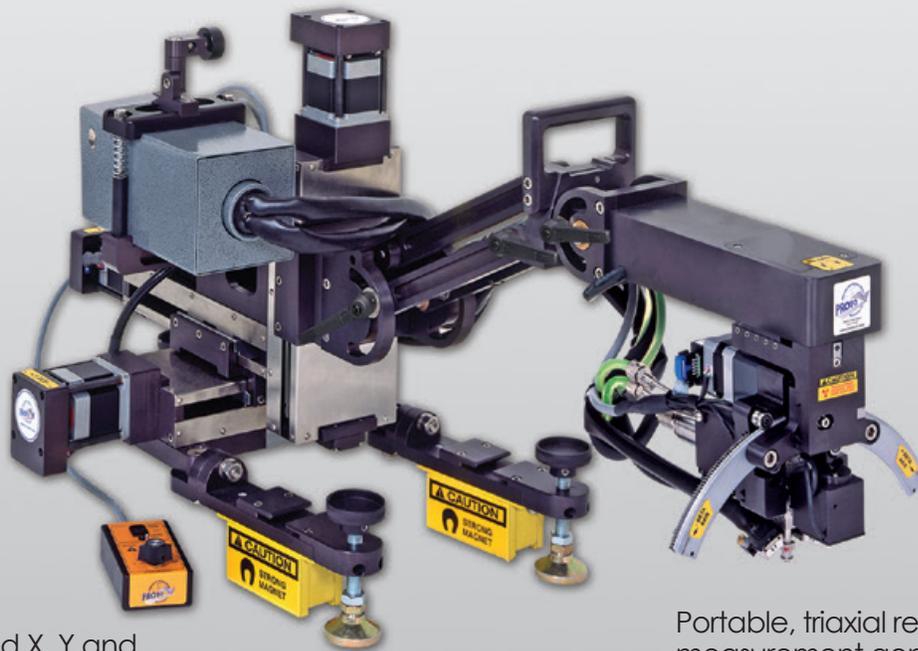
- distortion • Fatigue life • SCC potential
- Total stress (Residual + Applied)
- Weld residual stress maps
- Holes - effectiveness of cold work
- Fastener thread stress characterization
- Detect abusive machining
- Evaluate shot peening, LSP and LPB effectiveness
- Localized stress distribution characterization around fasteners
- Oil canning stress distribution due to machining practices



PROTO's patented Automated Residual Stress Mapping technology generates a comprehensive picture of the stress state of any sample. Even curved surfaces such as welds can be automatically mapped allowing designers and engineers to visualize and manage problem areas.

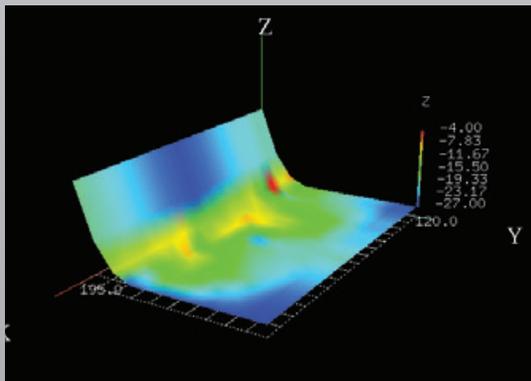


## MGR40 - RESIDUAL STRESS MEASUREMENT SYSTEM

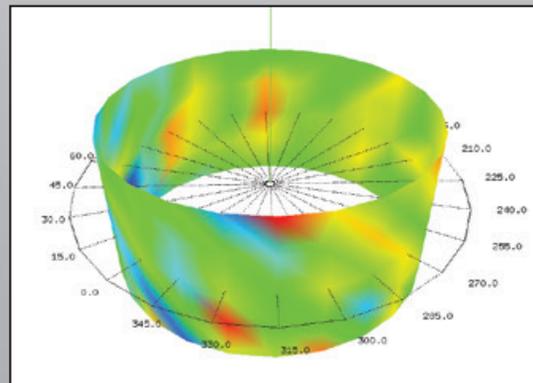


Fully automated X, Y and Z axes for portable residual stress mapping

Portable, triaxial residual stress measurement goniometer



Residual stress map on an aircraft frame



Residual stress map inside a trunion

## OPTIMUM COMPONENT & PROCESS DESIGN

Achieving full material potential requires quantitative measurement of residual stress for each individual component.

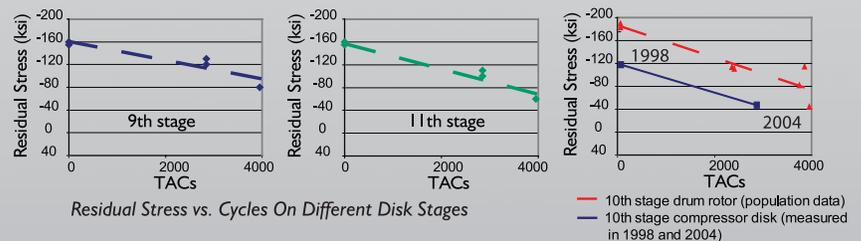
“Design to RS, Produce to RS and Manage to RS” is an enhancement concept to help achieve reduced component weight, improved life expectancy and lower maintenance costs. Achieving the full material potential, from alloys used in turbine components, requires measurement of failure critical areas on the “as manufactured” parts and monitoring these residual stresses throughout service life. The residual stresses must be measured to ensure beneficial stresses are present while detrimental stresses have been reduced or minimized.

## LIFE PREDICTION ENHANCEMENT: TRACKING LCF

Residual stresses can be an indicator of component life.

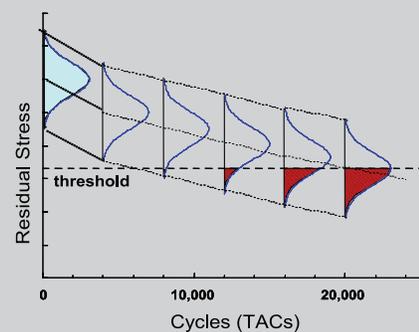
During the past five years, Proto has had the opportunity to measure RS on hundreds of turbine engine rotating components. Although the database of RS information is already sizable, considerable work lies ahead to expand this body of knowledge. Trends have been observed in the relaxation of RS with cycles and it is expected in the near future that such quantitative RS data will be used to enhance life prediction methodologies. Residual Stress Measurement is expected to be used as an important non-destructive determinant for life management decisions on in-service aero engine components subject to LCF.

Tracking residual stress of serialized critical components from the day they enter service and throughout their service life allows creation of a database to enable removal of parts for either reprocessing or retirement instead of entire populations. Engines can be rebuilt with critical parts with similar remaining life to optimize overhaul intervals. Life extension can be granted to components that have substantial RS credit. In addition, providing such information would allow a longer lead time and more efficient prediction of replacement part requirements.



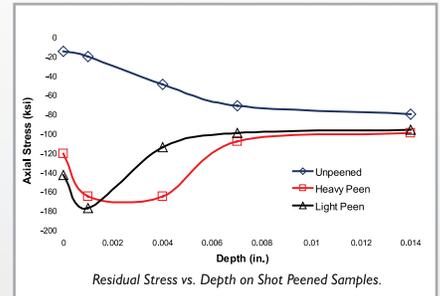
## RSM PATENTED DISK LIFE EXTENSION: LICENSING OPPORTUNITIES AVAILABLE

- Database tracks relationship between Residual Stress Measurement (RSM) and fatigue cycles (TACs).
- Evaluate health of each disk on its own merit and relationship within the statistical population.
- Remove disks with RS below the “threshold” as they are at risk to initiate a crack in the next service interval.
- Return disks to service with RS above “threshold”.

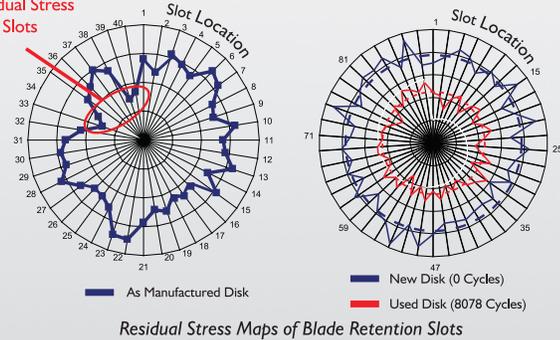


## PRODUCTION QUALITY: NONDESTRUCTIVE & QUANTITATIVE

Residual stress can be used for controlling production quality on the factory floor by detecting abusive machining, verifying effects of surface enhancements and evaluating heat treat effectiveness.



Low Compressive Residual Stress Slots



## EVALUATE HEAT TREAT EFFECTIVENESS

XRD can be used to determine that heat treatment processes are being applied correctly. Post heat treatment XRD residual stress measurement of components can ensure that residual stresses are being managed correctly thereby reducing issues such as distortion during machining or cooling strains.

## VERIFY SURFACE ENHANCEMENT PROCESSES

Turbine components often have complicated geometries that are enhanced by shot peening and other processes. XRD residual stress measurements can be used to verify that these locations have been enhanced to the specified residual stress level. A residual stress value, once established, can be specified on the engineering and processing documents and will attach an engineering value in stress rather than an Almen strip number designation.

## IDENTIFY ABUSIVE MACHINING

Machining can cause significant variations in the final residual stress state of a machined turbine component. XRD can be used to determine if any machined areas were subjected to abuse due to excessive tool wear, intermittent lack of cooling or aggressive machining practices. Abusive machining can create regions of tensile stress that could then become a potential source of crack initiation.

## MAINTENANCE IMPROVEMENTS

Prevent overpeening of disks during overhaul. Some in-service disks are shot peened during overhaul maintenance in an attempt to rejuvenate them. However, the residual stress level before the treatment is usually unknown and this could, unknowingly, have a deleterious effect on individual disks, especially if the disk is overpeened. The ability to measure residual stress enables maintenance staff to exercise better control and rework disks on a selective basis.



Measuring Residual Stress in a Blade Retention Slot



Measuring Residual Stress Inside a Bolthole



Measuring Residual Stress inside a Bore



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