



THE STRESSES OF AIRCRAFT SAFETY

When an aircraft component is manufactured, great care is taken to ensure the accuracy of the material's size, shape, and properties. Given the importance of these parts in maintaining the safety of aircraft, the consequences would be dire if the proper safety measures were not strictly adhered to. However, quality control processes do not just apply to the outward characteristics of the component; during the machining and fabrication of critical parts, invisible changes can occur within the material and render it unsafe after a period of use – namely, these would be changes to the residual stress state of the part. Because of the very likely possibility of introducing residual stress into an aircraft component during various stages of manufacturing, it is highly important for manufacturers and suppliers to understand what residual stress is, how to detect it, and how to ensure the safety of parts before and during use.

Residual stress is the internal stress locked into a component after all external loads have been removed. These stresses occur when a material establishes equilibrium after undergoing plastic deformation due to either inelastic

mechanical deformation, thermal loads, or phase changes. Residual stress can be either beneficial or harmful to a component. Compressive stresses are generally favorable, as they push the material together, while tensile stresses tend to be unfavorable, as they pull the material apart. In the absence of an external load, the total sum of all residual stresses in a part is always zero. More specifically, the net residual stress across any cross section is always zero; however, the distribution of stress can vary greatly. Therefore, identifying areas of high residual stress is critical in preventing premature failures.

It is also important to remember that residual stress is not the only stress that will be present in an aircraft component; during use, the part will also be subjected to applied stress, and the total stress present in a material is equal to the residual stress plus the applied stress. This is particularly important when the residual stress distribution results in high tensile stress in a region that will be subjected to high tensile loading, and similarly in regions of high compressive residual stress subjected to compressive loading.



When stress levels in aircraft components are too high, several different failure modes can pose problems. Firstly, **stress corrosion cracking** (SCC; also known as environmentally assisted cracking) is a potential source of failure that involves sustained tensile stress above a material's SCC threshold. Another common issue is fatigue, which can be divided into low-cycle and high-cycle fatigue (LCF and HCF). The terms are so named because of the number of cycles it typically takes for failure to occur – about 10^4 to 10^5 cycles for LCF and upwards for HCF. LCF typically involves high levels of localized loading, resulting in cumulative damage to a part and multiple crack initiation sites, along with changes in residual stress throughout the component's service life. On the other hand, HCF tends to involve lower levels of applied loading, eventually leading to a single crack initiation site caused by a defect, resulting in more abrupt changes in the residual stress state toward the end of the component's life. Other factors to consider are erosion – especially the combined effects of erosion and fatigue cracks – and creep,

the tendency of a solid material to move slowly or deform permanently due to persistent mechanical stresses. Over time, creep can result in fractures via creep rupture, and this process can be accelerated by high tensile stresses. Because so many failure modes are impacted by detrimental residual stress, manufacturers and suppliers need a reliable method of investigating residual stress states in as-manufactured components and predefined processes for repairing or replacing in-service components before failure occurs. Since high levels of tensile stress can contribute significantly to SCC, fatigue failure, and creep crack initiation, introducing beneficial compressive stress is a possible solution. The method chosen depends on the specific application, but some examples include shot peening, laser shock peening, burnishing, ultrasonic impact treatment, overspinning, and split-sleeve cold expansion. Some of these processes take place during fabrication of the components, while others have the potential to introduce favorable

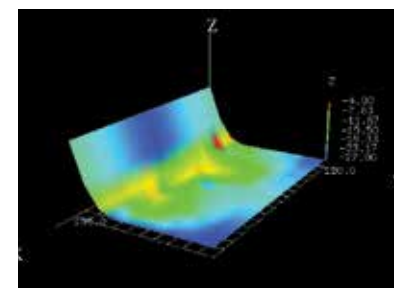
stress during service life – for example, during tear-down and inspection. When sufficient compressive stress is introduced in failure-critical regions, the in-service applied stress can be overcome, and the total magnitude of residual stress can be reduced to below the SCC threshold, fatigue limit, or creep rupture strength.

In order to determine the residual stress state of a component and prevent premature failure, a reliable, quantitative measurement method must be chosen. A widely accepted quantitative method that can measure residual stress without damaging the component is x-ray diffraction (XRD). XRD uses the distance between crystallographic planes (d-spacing) as a strain gauge. When a material is in tension, the d-spacing increases, and when a material is in compression, it decreases. The diffraction angle (2θ) is measured experimentally, and the d-spacing is calculated using Bragg's law: $n\lambda = 2d\sin\theta$, where λ is the source wavelength and n is an integer multiple of the wavelength. XRD measures at and near the surface, which

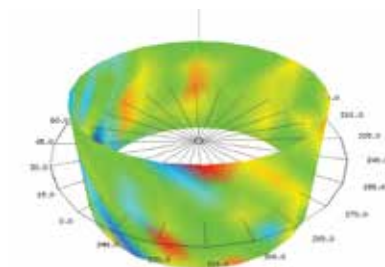
is necessary for investigating fatigue and SCC-related problems, since the near-surface stresses are most important in such applications. In addition, XRD can be portable, making it an efficient choice for repeated and/or field measurements. In a real-world application of residual stress testing using XRD, measurements were taken on airplane frames that were susceptible to stress corrosion cracking. According to the given specifications, the frames had been shot peened prior to testing. However, measurements performed both in the lab and in the field revealed that surface residual stress gradients were present, along with locally varying magnitudes of residual stress. These results were not consistent with shot peened components, as tensile stresses were identified instead of compressive stresses; in addition, shot peened components tend to exhibit homogeneous (compressive) surface residual stress rather than gradients. Based on these results, it could be determined that residual stress had not been adequately controlled upon fabrication of these components.

SCC

Along with high tensile stress, a susceptible material and a corrosive environment can contribute to SCC; however, these two factors can be difficult to alter. For example, removing the component from its environment is usually impossible, and adding a coating to effectively remove it from its environment is likely to be a short-term solution due to degradation of the coating.



Residual stress map on an aircraft frame



Residual stress map inside a trunion