Residual stresses are stresses which are retained in a stationary body at equilibrium with its surroundings. They are introduced into components or assemblies through thermal, chemical and mechanical processes. As such, most manufacturing processes (forging, machining, surface treatment, joining) introduce residual stresses that can be either beneficial (improved fatigue life) or detrimental (distortion, cracks). This makes residual stress characterisation critical to the success of process development. This paper looks into commonly utilised residual stress characterisation techniques and their application on surface enhanced materials typically used in aero-engines, where controlled distribution of residual stresses is a key desirable outcome. Almen measurements are currently relied upon heavily for estimation of the intensity of surface enhancement processes designed to introduce compressive residual stresses. While the Almen system is convenient, its ability to correctly predict the amount of stresses in the surface is not consistent, particularly when different materials are being considered. Residual stress characterisation removes such ambiguity by elucidating the actual distribution of residual stresses in the material that can be then directly linked to fatigue life. This paper discusses the relative advantages and disadvantages of alternative characterisation techniques that can be employed during surface enhancement process development.

**Introduction**

Manufacturing processes typically introduce residual stresses (stresses retained in the body and at equilibrium with its surroundings) through mechanical, thermal or chemical processes [1]. In welding for instance, the thermal gradient introduced by the locally intense heat and subsequent cooling generates large thermal stresses, some of which are retained in the body. Similarly, additive manufactured parts also suffer from large amounts of residual stresses that can result in part distortion or even cracks (see Fig. 1).

![Figure 1: The perils of residual stresses in additive manufacturing](image)

Residual stresses are introduced through mechanical means in processes like machining, extrusion and mechanical surface treatment. These processes generate plastic deformation in the material that in turn result in residual stresses in the body. They can be introduced as a by-product from the process (this is typically tensile residual stresses) or deliberately imbued to achieve certain desirable mechanical properties (usually compressive residual stresses). Machining of metallic alloys with low thermal conductivity like Ni based superalloys for instance typically results in high tensile residual stresses due to the large thermal gradient developed during the process.
Shot peening on the other hand generates compressive residual stresses through numerous impacts between spherical (metallic or ceramic) particles and the surface of the work piece. The forces from these impacts are sufficient to develop local plastic deformation beneath the free surface (usually around 100 – 200 µm deep). The compressive residual stresses generated by peening contribute to fatigue life extension by delaying the onset of crack initiation. It is also known that the distribution of these compressive stresses has a direct influence on the extent of fatigue life improvement in load-bearing parts. It is therefore critical to perform residual stress characterisation on shot peened parts to validate the process.

**Residual stress characterisation techniques**

Today, there are many characterisation techniques available for residual stress measurement. These techniques can be broadly divided into two categories, namely destructive and non-destructive. The destructive techniques rely on the measurement of relieved strain after cutting or drilling operations. One of the earliest method being developed was based on hole-drilling pioneered by Mathar in the 1930s [3]. Hole-drilling is now a mature technology and has been defined in an international standard [4]. The accuracy and repeatability of hole-drilling measurements have gone through significant improvements since it was first conceptualised. This was enabled by technological development in drilling, strain measurement (strain gauges, optical techniques, Electronic Speckle Pattern Interferometry (ESPI), digital image correlation) and finite element based stress computations [5]. Fig. 2 shows an example of an ESPI based hole drilling system. Cutting and slitting techniques have also been used for residual stress measurements using the same principle of mechanical strain relieving. The main advantage of destructive techniques are their relative low cost and ability to characterise bulk residual stresses.

![Figure 2: ESPI based hole drilling system by Stresstech (left) and speckle pattern used in determination of residual stresses (right)](image)

Several non-destructive techniques infer the residual stress through specific relationships identified between strain and material properties such as acoustoelastic and piezoresistivity in ultrasonic and eddy current residual stress assessments respectively. These techniques however, are largely limited by selectivity as the readings are influenced by a host of other factors besides residual stresses [6].

X-ray diffraction (XRD) techniques measure shifts in the diffraction angle, 2θ that can be related to lattice spacing, d (i.e. strain) according to Bragg’s Law. Unlike other non-destructive techniques, XRD does not suffer from selectivity issues as the lattice spacing can be directly linked to strain. This makes the technique suitable for residual stress characterisation for polycrystalline materials (most metallic alloys fall under this category). Residual stress analysers (XRD system optimised for residual stress measurement application) generally allow for measurements in the field as well as in the
laboratory. The system can also be mounted on a robotic arm to perform measurements on large components (see fig. 3).

The main limitations of this technique are the low penetration depth, which is limited to a few microns due to the low penetration of X-rays in most metals, and sensitivity towards crystallographic texture. There are several international standards available for residual stress characterisation via XRD. One that is widely used is the European standard, EN 15305:2008. A common accreditation available to measurement laboratories is ISO17025:2005. Such accreditation is particularly important to industry because of the need for clear traceability and quality assurance for each measurement. There are currently several centres around the world with ISO17025:2005 accreditation for measurements of residual stresses using XRD. The Advanced Remanufacturing and Technology Centre (ARTC) in Singapore is one such centre, serving customers in Asia Pacific and beyond.

![Robotic XRD equipment for residual stress characterisation on large components in Advanced Remanufacturing and Technology Centre (ARTC), Singapore.](image)

**Figure 3:** Robotic XRD equipment for residual stress characterisation on large components in Advanced Remanufacturing and Technology Centre (ARTC), Singapore.

### Residual stress characterisation for development of peening processes

Controlled residual stress distribution is a key desirable outcome of peening processes. Specific stress profiles are usually prescribed for different parts to optimise their fatigue performance. A stress profile can be adequately described using three quantities namely depth of influence, surface and maximum stresses (see Fig. 4). The influence of different peening parameters on residual stresses is also shown in Fig. 4.

A peening process is typically developed for each individual part because of differing material, geometry as well as residual stress requirements. Whilst peening processes are typically prescribed using Almen intensity (i.e. deflection of a thin strip of SAE1070 steel) and coverage (i.e. percentage of area covered by shots indentation), the desired outcome of the process remains the final stress profile. This renders residual stress measurements essential in determining the correct set of peening parameters. Examples of stress profiles obtained from peened surfaces of In718 are shown in Fig. 5.

In this particular case, air pressure was varied between 0.052 and 3.85 Bar whilst keeping the mass flow rate of media constant which translate to an intensity range between 0.006 and 0.018 inch-A. Some of the critical criteria for peening are depth at which the maximum compressive stress is located as well as the location of the transition between compressive and tensile stresses (depth of influence). Both quantities were shown to be inter-dependent and correlate well with peening intensity (see Fig. 6).
Comparison of residual stress characterisation techniques

Stress profiling was carried out on a peened surface using three different techniques namely XRD, centre-hole drilling and ESPI hole drilling. The results obtained from the different techniques (see Fig. 7) show good agreement to each other, suggesting that different characterisation techniques can be utilised for process development. Generally, two areas must be considered when appraising the data obtained from the two techniques (XRD and hole-drilling). First of all, residual stresses being characterised here are an averaged value obtained from the finite sampling volume. This quantity varies significantly between the two techniques, but given the relative uniformity of the stress states in
the peened surface, the impact on residual stress readings is likely to be negligible. Secondly, the XRD technique measures strain from a particular crystallographic phase rather than the bulk to obtain stresses. Therefore multiple measurements may be needed when measuring residual stresses on a multi-phase material.

![Graph](image)

**Figure 6: Peening intensity vs depth at maximum residual stress and depth of influence**

![Graph](image)

**Figure 7: Comparison of stress profiles obtained from three different characterisation techniques.**

**Rapid residual stress characterisation**

The \( \sin^2 \Psi \) method is a commonly used diffraction based method for residual stress measurements. This technique requires multiple X-ray exposures to establish a plot of \( d \) (lattice spacing) vs \( \sin^2 \Psi \) from which residual stress is computed. This translates to a measurement time of around 10 - 30 minutes per measurement depending on the material as well as measurement parameters. As the need for measurement increases, particularly when residual stresses are integrated into parts’ quality
assurance, reduction of measurement time becomes highly desirable. This can be realised through a
diffraction method based on a $\cos \alpha$ technique developed that looks into the entire Debye-Scherrer
ring [8]. Commercial systems using $\cos \alpha$ technique have subsequently been developed [9] and
produce results that demonstrate good agreement with the $\sin^2 \Psi$ method [10, 11]. Utilising this
technique, a measurement can be completed within 2 minutes through a single exposure, drastically
reducing the amount of time required per measurement. This will also pave the way towards
integration of residual stress characterisation in manufacturing processes for quality assurance.

Conclusions

Residual stresses present a challenge to manufacturers particularly because they are not easily
detected and have severe implications on mechanical performance. When carefully managed and
controlled however, residual stresses can be exploited for improvements on fatigue performance
which is a major failure mechanism in engineering components. The ability to alter as well as
characterise residual stresses represent big opportunities for cost reductions. Two major considerations
have to be taken into account when selecting a suitable characterisation method. First of all, the
characteristics of the part to be measured (geometry, size as well as microstructural properties such as
grain size and crystal orientation). Secondly, the accuracy and resolution requirements from the
characterisation. The three techniques presented in this paper (XRD, centre hole-drilling and ESPI
hole-drilling) were found to be in a good agreement for measurements on a shot peened surface. The
major advantage of XRD in this case is the ability to measure stresses at the free surface while the
hole-drilling techniques allow for a much faster data acquisition (approximately 10 - 20 times faster
compared to XRD depending on factors such as material and layer removal requirements).

References


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means of image plate for laboratory X-ray experiment,” *JCPDS - International Centre for