Quantitative Residual Stress Measurements for Improved Quality Control and Process Optimization in Gears and Additively Manufactured Components

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Introduction

The required endurance and performance of gears (and many other components) are increasingly more demanding. Designers are tasked with improving capacity, fatigue strength and lifetime while still managing weight and cost. Enhancements are being found in changes to geometry, heat treatment and surface modifications, just to name a few. The research and development of gear modifications is aided in large part by sophisticated modeling and analysis software. Efficient development requires validation techniques and testing, which yield data-rich results and quantitative feedback. Manufacturing these ever-more complex geometries with increasingly tighter tolerances dictate that inspection and control methodologies and technologies advance accordingly as well. In this article, the focus is put on one technology, X-ray diffraction (XRD), and more specifically, residual stress measurement by way of XRD for both process development and quality control.

Almost all manufacturing processes introduce residual stresses, of which some are beneficial, and others are detrimental to component performance and longevity. Historically, residual stresses have been an afterthought in component design. However, current trends in light-weighting, miniaturization and focus on manufacturing costs have placed a greater importance on the topic. The proliferation of additive manufacturing techniques, some of which are notorious for creating parts having near (or above) yield residual stresses, has made the ability to characterize, optimize, and control residual stress a necessity.

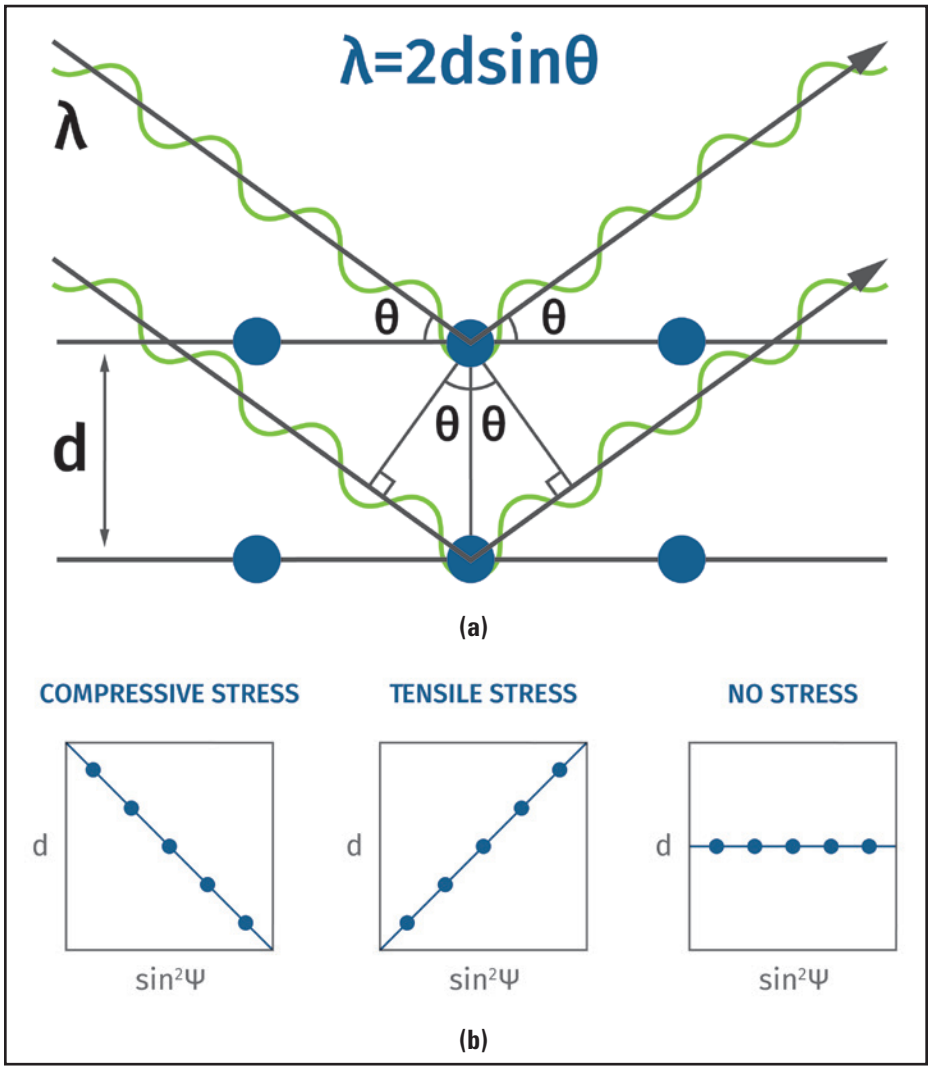

Figure 1 a) Illustration of X-ray diffraction as described by Bragg's Law; b) *d* vs $\sin^2\Psi$ plots from compressive, tensile and neutral stress states.

Residual Stresses and Their Importance

While the term *residual stress* is well known and generally understood, it is helpful to revisit the definition and reiterate the important role residual stresses play in modern gear design and manufacturing. Residual stresses are the stresses which remain in a material volume after all external loads are removed. They develop as an elastic response to incompatible local strains (Ref. 1). For example, during shot peening the surface layer is plastically deformed and thus looks to expand. The underlying material restricts this expansion (local strain) and thereby holds the surface and near

surface material in a state of compression. These relatively shallow, sometimes high magnitude, compressive stresses are balanced out by tensile stresses acting on the interior volume of material.

Common mechanisms for creating residual stresses and some typical manufacturing processes and in-service events associated with these mechanisms include (Ref. 1):

- Non-uniform plastic deformation — forging, bending, rolling, and in-service surface deformation
- Surface modification — machining, grinding, peening and corrosion or oxidation
- Material phase and/or density changes — typically a result of large thermal gradients from welding, heat treatment/quenching, and frictional heating during machining or in-service

Residual stresses are no less important than applied stresses. In practice "total stress," which is the summation of residual and applied stress, should be considered. In the total stress equation, both residual and applied stress are weighted equally. For example, in shot peened gear teeth, the near surface compressive residual stress counteracts the large tensile loads encountered on the flank surface during tooth bending, thereby effectively reducing the net effect or "total stress." In practice the influence of residual stresses on performance are more nuanced, and thorough characterization and control of residual stress is required.

X-ray Diffraction Residual Stress Measurement

There are several methods capable of providing near surface residual stress information. XRD is an accurate and practical method for quantifying near surface residual stresses such as those developed during shot peening and other similar surface treatments. XRD also has several advantages as related to other mechanical, ultrasonic, or magnetic methods available (Ref. 2). In addition, industrial standards for the technique have been published by EN, ASTM, and SAE, further establishing the method for surface and near surface stress characterization (Refs. 3–5).

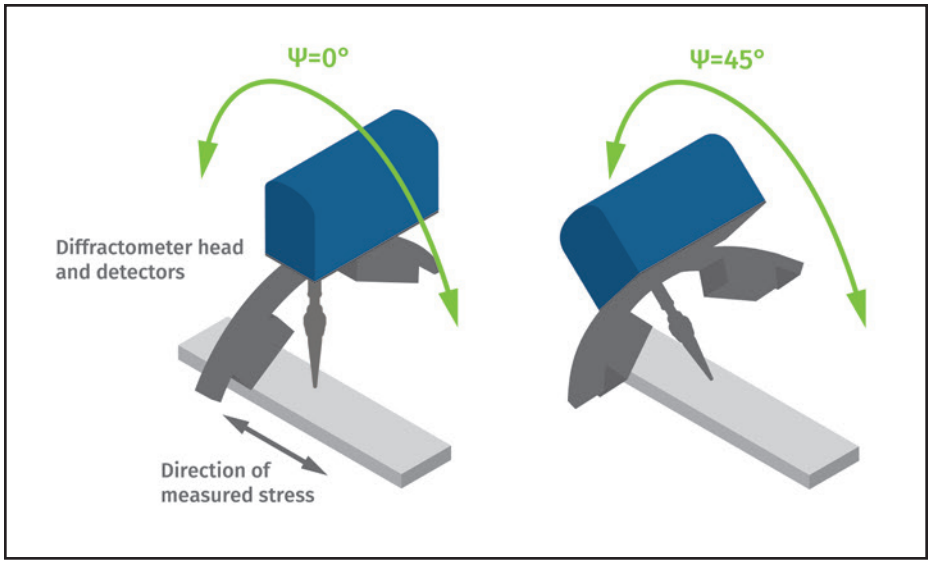

Figure 2 Illustration of a diffractometer head measuring at two different psi angles and the associated direction of measurement.

X-ray diffraction, as the name implies, requires the utilization of electromagnetic radiation known as X-rays. X-rays are higher in energy but shorter in wavelength than visible light. As such, they can be used to probe the inter-atomic distance of most crystalline materials, typically penetrating between 1 to 10 µm into the surface of a given material. The X-rays utilized in residual stress measurements are commonly referred to as "soft," as they are lower in energy than the "hard" X-rays commonly used in medical imaging. For most commercially available XRD equipment, the X-ray power is low and safe working distances are short (6–10 feet). Nevertheless, safety precautions and interlocked systems are typically utilized.

X-rays diffract from the crystallographic lattice of a material at an angle equal to 2θ as governed by Bragg's law. As shown in Figure 1a, λ is the wavelength of the incident X-rays, θ is the diffraction angle and d is the lattice spacing of the crystal planes. Therefore, if the wavelength is known and the diffraction angle is accurately measured, then the lattice spacing can be easily calculated.

By assuming a planar stress state in the measured volume, the lattice spacing in the direction normal to the surface (Ψ = 0°) can be used as an un-strained reference. This removes the need for a stress-free reference sample. The diffraction angle is then recorded for different, non-normal angles commonly referred to as Ψ angles or tilts as illustrated in Figure 2. Comparing the measured diffraction angles (θ) and change in lattice spacing (d) recorded at each angle gives a linear distribution of d vs. $\sin^2\Psi$, as shown in Figure 1b. This information, combined with the appropriate material parameters (Modulus and Poisson's ratio), yields the stress in the direction parallel to the plane of Ψ tilting. Any in-plane direction of stress can be measured by simply rotating the sample, or the diffractometer head. It is important to note than by measuring in three independent directions (at a single location) the planar principal stresses can be determined.

In many cases, surface residual stress alone is not enough. For instance, as shown in Figure 3, an abusively ground component can have compressive residual stress on the surface. It is the presence of sub-surface tensile stresses which leads to early failure. This stress vs. depth information can be acquired by incremental layer removal and subsequent XRD measurement of each new free surface. This process is commonly referred to as an XRD residual stress depth profile. Layer removal is commonly achieved by localized electrolytic so as not to introduce new stresses or cause noticeable redistribution of stresses elsewhere in the sample. There are, however, corrections available when necessary (Ref. 6).

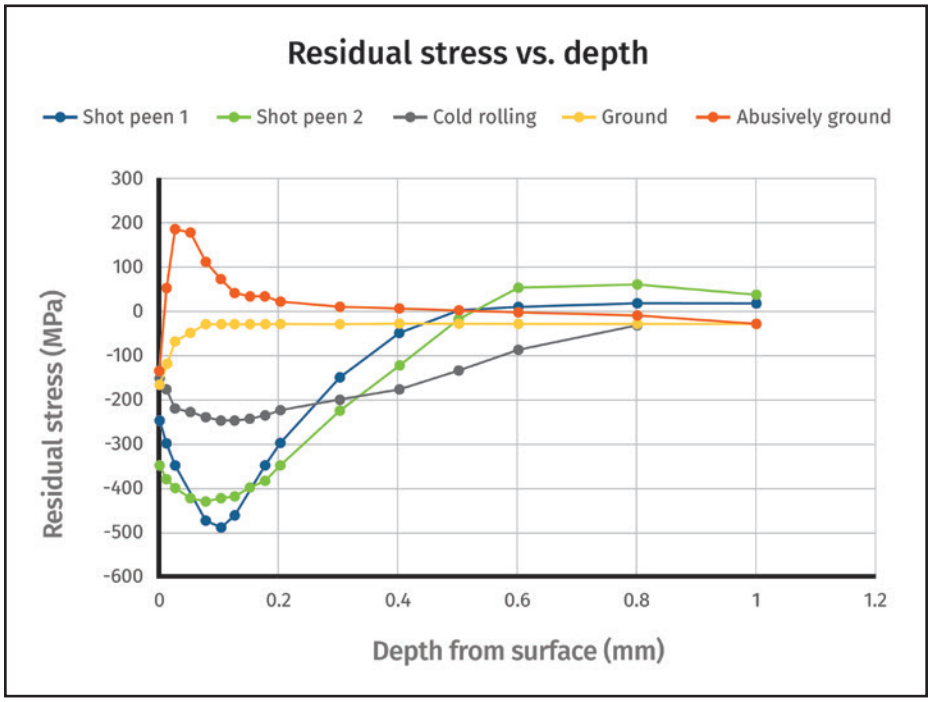

Figure 3 Example residual stress depth profiles for common processes in steel components.

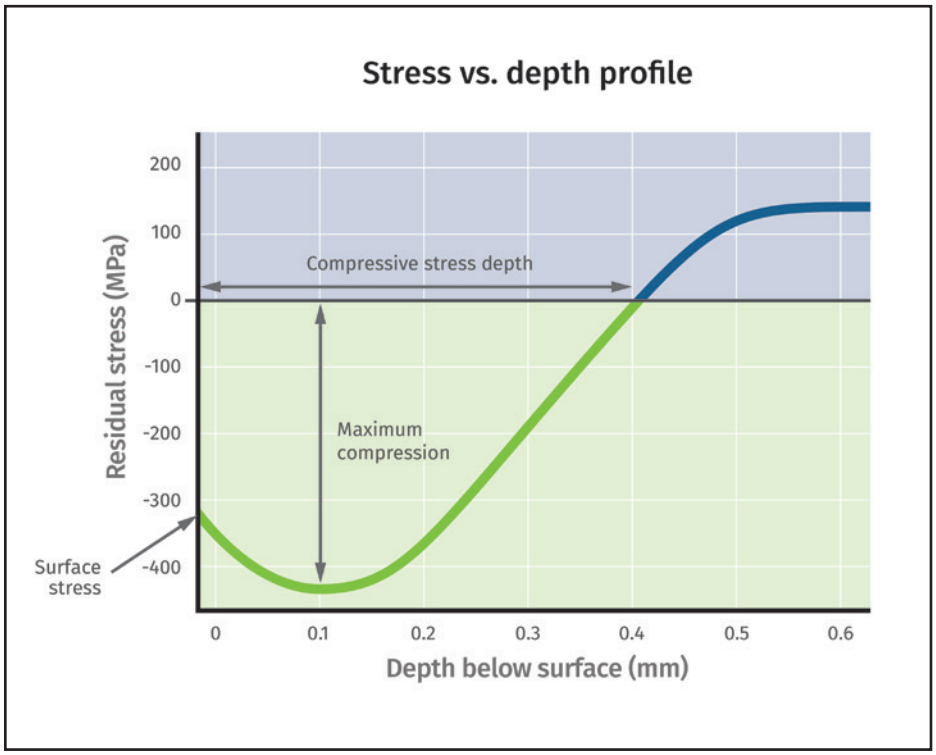

Figure 4 Characterisitcs of a shot peen induced residual stress depth profile.

Typically, XRD depth profiles are limited to a final depth of approximately 1 mm, but under proper circumstances measurement can be made to greater depths. For many manufacturing processes, such as those shown in Figure 2, 1 mm is well beyond the depth needed to thoroughly characterize the induced residual stresses.

XRD for Quality Control in Shot Peened Gears

Shot peening typically results in an easily recognizable U-shaped curve. Shot peen induced residual stress depth profiles have several common characteristics. The surface stress is always less compressive than the stress acting on the material immediately below the surface, due to the excessive cold working and plastic deformation. The profile reaches a maximum compression, at some specific depth, and then increases until crossing the neutral axis. This point designates the compressive stress depth. Slight changes in any of these characteristics (magnitude, depth, gradient, etc.) can result in significant effects on a component's longevity.

Shot peening processes have traditionally been established and controlled using Almen intensity. Almen strips are specified pieces of metal which are deformed during peening of one side. The height of deformation or arching is carefully measured and then related to peening intensity and coverage. This method is widely used, and specific standards are available (Ref. 7). The method does, however, have several limitations. Almen intensity is essentially a measure of the area under (or above) the stress profile curve. Therefore, equivalent Almen intensities can be obtained from two peening processes which produce significantly different stress vs. depth profiles: the two shot peen profiles shown in Figure 3, for example. For manufacturers which have identified stress profile characteristics as critical measures of part performance, such as surface stress, maximum compression or maximum compressive depth, a more capable inspection is required. XRD residual stress depth profiles provide the necessary information.

For example, a gear manufacturer determined that previously undetected variation in their shot peening process led to early fatigue failure in several

products. Through subsequent review and development, they established specific requirements on the compressive residual stress-depth profiles required to meet the expected part life cycles for several gear types. These limits and tolerances were determined through modeling, XRD validation and fatigue testing. Next, they implemented XRD residual stress inspections to verify that these newly established standards were being met in manufacturing. The following steps and Figure 5 explain the inspection process which was integrated.

1. Section sample for accessibility
2. Align sample and reference depth gauge
3. Measure radial (root-to-tip) stress, σ_0, at exposed flank surface
4. Electrochemically remove material to a depth, D_1
5. Measure radial stress σ_1
6. Electrochemically remove material to a depth, D_2
7. Measure radial stress σ_2
8. Print report showing pass/fail determination, proceed accordingly

In the above, $D_{1,2}$ refer to specific depths that are determined separately for each gear type measured and $\sigma_{0.1,2,}$ are the residual stresses measured in the radial direction at each respective depth. In this case, a tolerance of ±0.005 mm was placed on each measured depth. This precision is met with relative ease using preprogrammed electropolishing parameters (time, flow, voltage, etc.) which are customized for each gear type and required depth. The depth tolerance provides insight into the level of control necessary to insure part quality/performance.

Inspections are completed using a customized solution, like that shown in Figure 6, with combined safety enclosure, sample trolley, and integrated electropolish station. One part per peening lot is tested and the duration of the process (steps 1–8 above) take approximately 40 minutes with sectioning accounting for 10+ minutes depending on the size of gear being tested. The geometry and size of gears being tested requires that portions of the gear are sectioned for appropriate accessibility of the incoming and diffracting X-rays. Part specific measurement routines (tilt angles, exposure times, etc.) and electropolishing parameters were preprogrammed, making steps 3–8 nearly push-button. This, in combination with straightforward pass/fail acceptance limits, allows measurements to be performed by non-technical operators without the need to analyze diffraction patterns or assess characteristics of the measured residual stress-depth profiles.

This specific application is shared to highlight the capability of XRD for both establishing and controlling residual stress requirements. Furthermore, it illustrates the evolution of the technology from a formerly time- and skill-intensive technique to one which can now be utilized in a manufacturing environment for high precision quality control with reasonably low investments in time, cost and effort.

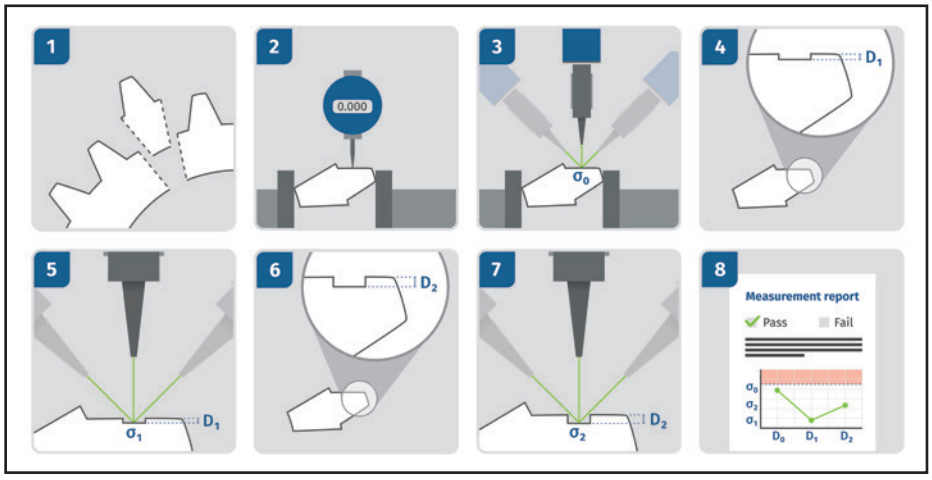

Figure 5 Illustrated inspection process steps 1–8.

1. Section sample for accessibility, 2. Align sample and reference depth gauge, 3. Measure radial (root-to-tip) stress, σ_0, at exposed flank surface, 4. Electrochemically remove material to a depth, D_1, 5. Measure radial stress, σ_1, 6. Electrochemically remove material to a depth, D_2, 7. Measure radial stress, σ_2, 8. Print report showing pass/fail determination, proceed accordingly

Figure 6 Commerical off-line XRD inspection station.

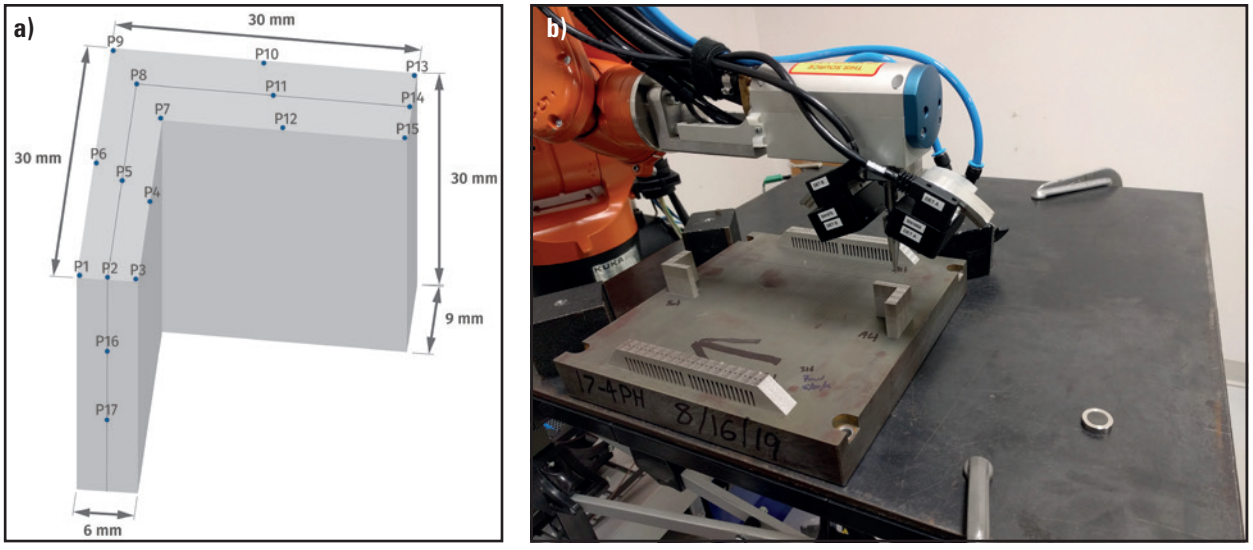

Figure 7 a) Diagram of residual stress measurement locations on sample under test; b) additive samples on build plate during XRD measurement.

Additional Applications

While XRD is well suited for characterizing stress in common steels, it can be used to accurately measure near surface stress in nearly any crystalline material. The applications are vast and constantly increasing in complexity and breadth. Amid the increasingly more popular industry that is additive manufacturing (AM), it is important to explain that XRD is capable of measuring residual stress in most metal additive components just as with most traditionally manufactured metal parts. This includes processes such as directed energy deposition and powder bed fusion.

In these cases, as with most AM processes, each component is built through successive layer-by-layer melting. The resulting cyclic thermal loading and temperature gradients can result is relatively high magnitude residual stresses. It is common for these stresses to result in warping, cracking or layer delamination (Ref. 8). As a result, an increased importance has been placed on the comprehensive understanding of residual stress formation in AM, especially as an increasing number of structural AM components are being utilized in the aerospace, automotive and medical device industries.

The factors affecting residual stress in AM parts are many, and the topic is a very active area of research. In some applications unfavorable stresses are remediated by post-process heat treatments and/or surface treatments such as peening. Some are investigating in-situ controls while others look to find optimal build parameters via modeling. Regardless, validation is necessary and the most widely utilized techniques for measuring residual stress in AM parts are X-ray and Neutron diffraction (Ref. 9). The latter can be used for 3D, volumetric analysis of residual stresses; however, the method is severely limited by the instrumentation required, i.e. a nuclear reactor. While slightly less capable, XRD instruments and measurement services are readily available through commercial equipment suppliers or accredited service measurement providers.

The following provides a straightforward example of XRD residual stress measurements for AM model validation. Researchers at the University of Pittsburgh aimed to develop an alternative method for determining the J-factor of as-built Inconel 718 samples as the standard test method isn't practically applicable for parts manufactured via laser powder bed fusion for various reasons (Ref. 10).

Their modified approach required the creation of a residual stress simulation and subsequent experimental validation of said model. Samples were printed using specific parameters and a total of seventeen (17) locations were selected for XRD residual stress measurements. These measurements consisted of both surface stress and stress-depth profiles. Figure 5a shows the specified locations and 5b the sample during measurement. Table 1 presents the predicted and measured principal stresses. In this case, the agreement was satisfactory and provided the validation necessary to confidently

Table 1 Comparison of numerically predicted residual stress values to experimentally measured (XRD) values

Measurement position	Principal stress Simulation predicted (MPa)	Principal stress Measured XRD (MPa)	Prediction error (%)
P1	147	146	0.7
P2	167	182	8.2
P3	148	139	6.5
P4	505	455	10.9
P5	636	644	1.2
P6	501	490	2.4
P7	592	548	8.0
P8	635	653	2.8
P9	312	342	8.8
P10	518	721	28.2
P11	635	699	9.2
P12	511	358	42.6
P13	318	681	53.2
P14	560	612	8.5
P15	320	447	28.4
P16 (1.0 mm)	87	193	55.2
P17 (1.0 mm)	673	751	10.4

proceed with their simulated approach to determining fracture characteristics in additive parts.

Summary

Residual stresses play a crucial role in modern manufacturing. Carefully engineered surface stress profiles can yield significant performance advantages in various components. Alternatively, undiagnosed detrimental residual stresses can lead to diminished load capacity, reduced part life and catastrophic failure. XRD is an accurate and reliable method of measuring residual stress. XRD residual stress measurements are indispensable, whether validating numerical simulations or verifying in-line production processes. Technological advances and commercially available hardware as well as accredited measurement service providers have made XRD accessible and affordable regardless of application.

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