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An Overview of Techniques for Measuring Residual Stress in Metal Matrix Composites

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Abstract

Measurement of residual stress is significant to ensure safety, reliability and the life of composites, and currently has been a hot issue in scientific research. The fabrication processes such as machining, and heat treatment inherit either kind of residual stress which had either positive consequences or negative ones, for example, the fatigue limit of a component enhances by compressive stress, whereas corrosion resistance gets reduced by tensile stress. This study is aimed at a brief overview of the recent advancement in this field to help researchers in the in-depth study of measuring residual stress. It helps them in selecting the most appropriate techniques among destructive methods *i.e.*, mainly Contour, ring core, deep hole-drilling method, and non-destructive techniques *i.e.*, diffraction, ultrasonic method, depending on their requirements and applications. For each available technique, working methodology, physical limitations, and applications are discussed. At the end of this paper, future trends regarding an assessment of residual stress have been forecasted.

Keywords

Residual Stress, Destructive Methods, Compressive Residual Stress, Tensile Residual Stress, Non-Destructive Methods

1. Introduction

For structural and industrial applications, a single material is not fulfilling the demands for required strength, stiffness, corrosion and fatigue resistance, flexibility, and life. Therefore, a combination of a different class of materials leads to the production of composites that introduce superior properties over single constituent material. Composites are composed of two main elements such as matrix and reinforcement. The properties of composites are classified based on bonding between two constituent phases. Composites are mainly formulated at high temperatures and under certain loading so curing from high to low temperature introduced a mismatch in the coefficient of thermal expansion in matrix and reinforcement leading to introduce surface and internal residual stresses. These stresses might be compressive or residual. Compressive stresses contribute to adding in mechanical properties while residual ones deteriorate the quality of inherent physical properties. Therefore, it is crucial to figure out residual stress in designing and modeling composite materials to overcome premature and catastrophic failure. In this paper, we have briefly discussed the techniques available for the measurement of residual stress in composite materials.

The induced stresses that remain stationary within a material at equilibrium with its surroundings even on unloading are known as residual stresses. Fabrication techniques such as machining, and heat treatment generate elastic and plastic deformation in the structural component as a result of varying temperatures and applied stress, or using any chemical action in the process. Residual stress is the result of elasto-plastic deformation due to thermal and chemical volumetric changes in a component [1]. Residual stress can be very dangerous for the performance of the material and the life of a component. Residual stresses are outlined as micro and macro stresses that can be found in any material at any time. Macro-stresses are termed as type 1 and developed in several grains, micro stresses are termed as type 2 and developed in one grain while sub-micro stresses are termed as type 3 and developed within several atomic distances in grain. **Figure 1** shows the distribution of all three types of residual stress in apolycry stalline material.

Tensile residual stresses have adverse effects on structural properties of material mainly fracture life, mechanical distortion, dimensional stability, and corrosion resistance. A huge amount and effort are required in removing these defects and repairing the components from failure. For instance, qualities of metal matrix, such as additive manufacturing are vulnerable to residual stresses, which in turn, can adversely impact mechanical performance and fatigue life in services.

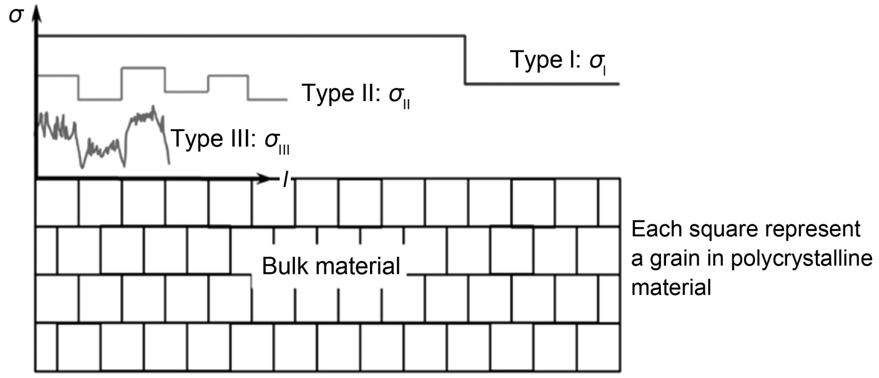

Figure 1. Development of different types of residual stress in polycrystalline material.

Therefore, the use of thermos-elastic mechanics, prior works on sources of residual stresses, and others seem to be beneficial to mitigate these stresses [2]. Redistribution of stresses can decrease the stiffness and stability of components and leads to a reduction in the deformation of components.

Measurement of residual stress is very much important in industry so measurement techniques are old as the 1930s, and dozens of methods are being developed subsequently. Research shows that some recent progress in measuring residual stress is made in contemporary times. Among destructive and non-destructive testing methods in context of residual stress measurement to alleviate its negative effects on material properties, some pristine methods can be nano-indentation technique, ultrasonic method, magnetic methods, and more [3]. Mechanical destructive involves the mechanical removal of material by either destructive or semi-destructive means. The most common destructive techniques are contour method, ring-core method, sectioning, and deep-hole methods while ultrasonic methods, diffraction methods (X-ray diffraction, neutron diffraction), and magnetic methods are listed as non-destructive techniques [4].

This paper discusses the methods for the measurement of residual stress in composites. In the end, several development trends in measuring residual stress are also discussed briefly.

2. Method Selection

Considering the level and location of stress is very important along with the component's limitations such as dimensions, and location of the stress in the component, and determine if it is possible to access the targeted point without disturbing the stress state or not.

This paper provides a quick review of available techniques for the measurement of residual stress in composite materials. It briefly listed the working criteria, applications, and limitations for each method. The general classification of techniques for the measurement of residual stress is shown in **Figure 2**.

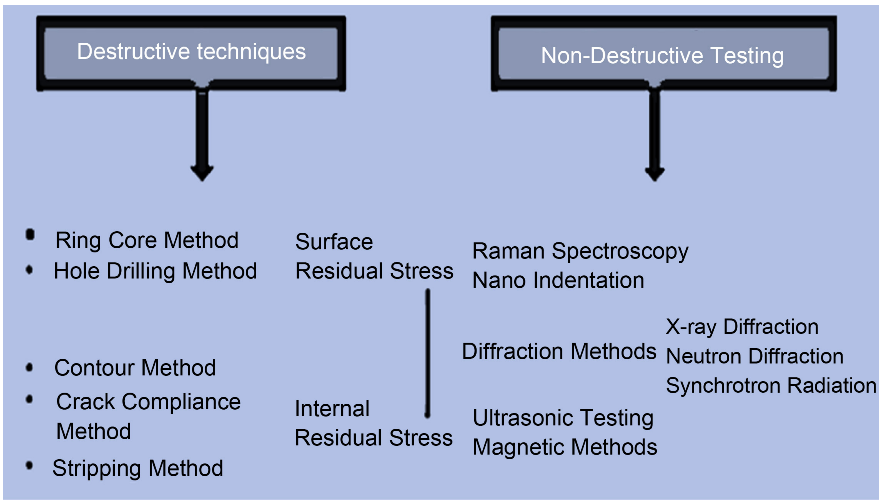

Figure 2. Schematic of general classification of residual stress measuring techniques.

2.1. Destructive Methods for Measuring Residual Stress

Residual stress can't be measured directly, indirect parameters *i.e.,* strain, area mapping, and force applied/induced are calculated for related stress measurement. The Destructive testing method is the earliest technique and had been used over decades due to its high accuracy and practicability in practical applications. The destructive test method removes the sample material by a semi-destructive or completely destructive method and the residual stress adjacent to the displacement or strain remains in the area. Cerit [5] examined the impact behaviour of Al 2124/SiC composites having single and double particle size SiC particles. It was determined that the composites containing double particle SiC show better impact resistance compared to the single particle ones. The residual stress map of the surface layer cannot provide accurate strength analysis because surface stress cannot effectively show the effect of the processing treatment, so it demands development of more disciplines and techniques. From measurement of surface tension to residual stress measurement leads to the progress of the development of destructive residual stress tests.

2.1.1. Sectioning Technique

"Sectioning method", relies on the fact that "by cutting the smaller cross-section of a specimen into many strips relieves the internal stresses being developed in a sample".

Figure 3 shows the sectioning and slicing of the component. From figure, we

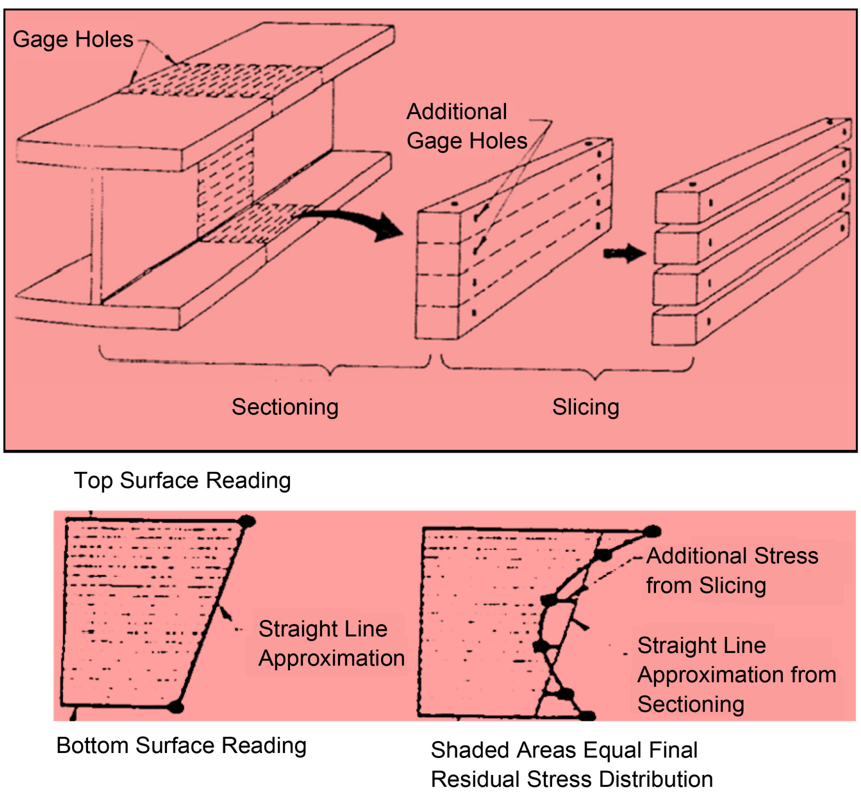

Figure 3. Estimate of residual stress distribution by slicing and sectioning method.

came to know how slicing helps in the calculation of additional residual stress along with the sectioning technique. The sectioning method is widely applicable for specimens where only longitudinal stress is measured. *Hooke's Law* is used to measure the change in length of each strip so we can calculate the stress distribution over an area with adequate accuracy. To relieve the residual stresses present on the cutting line, a cut is marked on the instrumented plate. The cutting process should be carried out wisely so it would not add any plasticity or heat to the cutting planes so that the original existing residual stress in the sample can be measured. The dimensional changes that occur during stress relaxation are always purely linear elastic, this fact leads to the computation of relaxed stresses from strain measurement [6]. The temperature variation causes errors in this technique which can be removed by using reference bar of the same component under investigation. The strains in the specimen are read at bottom and top surfaces. In sectioning, many measurements from experimental data are taken and calculation of residual stress at the top and bottom surfaces is computed using computer programs that plot the resulting data.

The existing knowledge of the approximate variation in residual-stress distribution is required so "partial sectioning" can be utilized for reducing the total member of required longitudinal sectioning. Research unveils that directional as well as an oscillation of residual stress can be ensured by laser metal deposition processes [7]. However, this destructive technique only gives average stress over an area from where it is removed. Cross-section of the specimen can no longer change balancing compressive stresses, and therefore, residual stresses can be handled [8]. Sectioning is accurate and applicable for the measurement of longitudinal stresses in engineering components. In structural components with "*welded joints*" sectioning is preferred.

The sectioning method requires many calculations and measurements which may have chances of personal error so standard computer programming is needed to calculate accurate results.

2.1.2. Hole Drilling

A hole-drilling method is one of the most popular ones, which is conducted by making a small hole in the surface of materials. Eventually, it relives residual stress as well as relative deformations around the hole on the surface of the plane. This specific method shows that residual stress in a perpendicular direction is relatively high than stress prevailing in the plane, which can also evaluate a tri-axial stress state through this method [9]. In hole drilling when some part of the material is removed, stress relaxation occurs and residual stress can be computed through the induced local deformation. From the surface to depth measurement of residual stress hole-drilling stress analysis has become a very sensitive and versatile method. A strain-gage rosette is required in this process. It had three gages arranged systematically at 0, 90, and 135 degrees respectively. This rosette is glued to the part where a hole is required to be made. The hole is drilled around a centre point where the rosette is placed. While drilling a hole drilling speed should be taken into account. The speed shouldn't be Ultra-high, which only accepts the smaller mills. The required milling speed required to produce holes without introducing new stresses in the sample is around ~200,000 rpm. This method has easy computing power and can measure residual stress up to the depth of 2 mm or more.

The maximum depth sensitivity of the three strain gages built into the strain rosette is approximately 0.7 times the diameter of the hole. The hole drilling method measures the in-volume stresses, the near-surface volume stresses can be very small, with a depth of cut carefully controlled. The computational results comprise hear, principal, and biaxial stresses for each of the layers. **Figure 4** shows the distribution of residual stress components in the hole-drilling process.

In a study of improving the application range and accuracy, Chen et al. study the influence of Poisson's ratio on the strain release factor and established a modified formula considering Poisson's ratio. The relative error between the residual stress value obtained by the modified method and the actual value was less than 1% [10].

For uniaxial strain measurements, hole drilling is considered a more accurate and economical method than X-ray layer removal technique which costs 4 to 10 times more per location measurement. Hole drilling is also applicable for measuring residual stress in materials with good wear resistance.

It is a destructive technique with uncertainty increased while measuring stresses greater than 80% of yield caused by plastic relaxation. Depth determination is less accurate and σzz cannot be measured. It is applicable only to flat surfaces and is highly sensitive to non-concentricity between the drilled hole and the SGR (Special strain gauge rosette).

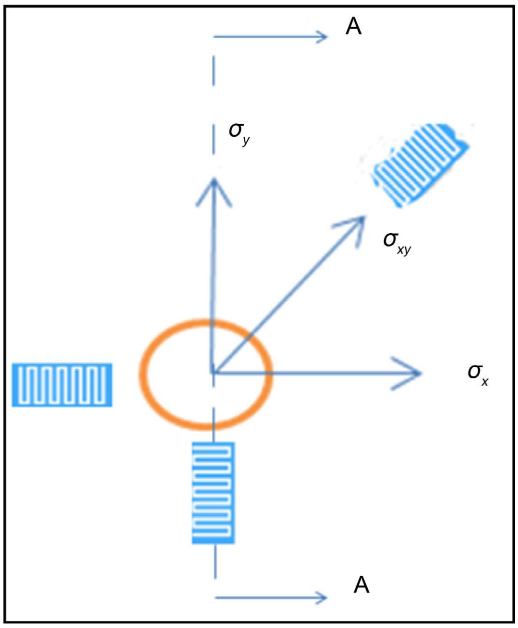

Figure 4. Components of residual stress during hole drilling.

2.1.3. Ring Core Method

In this technique, residual stress is measured over depths from the near-surface to bulk areas. Relaxation effect of the core is used to measure macroscopic residual stress and the relaxed strain is measured at the surface of the core with the help of a three-element rectangular rosette in the common direction. Residual stress in laminated materials and composites can be estimated using the ring core method [11]. Due to its portable nature, it can be applied in a field and used in the quality control department as well. It can be used in labs, in sites, and anywhere else depending on the specifications.

Ring core measures residual stress from near-surface to bulk regions for both metallic and non-metallic materials with low eccentricity error sensitivity. The Nominal accuracy of ring core: 10 MPa—Aluminium, 30 MPa—Steel, 15 MPa—Titanium. Ring core method measures bi-axial residual stress distribution (e.g., σxx, σyy and τxy), including stress gradients. It has a high depth of investigation and is sensitive to strains. It is a relatively quick and easy process to apply. Further research exhibits how Focused Ion Beam-Digital Image Correlation (FIB-DIC) ring-core stress measurement along with eigenstrain modelling can be a couple of novel approaches to separate residual stress [12]. Besides, electrochemical polishing is a surfacing preparation method, which satisfies force as well as moment equilibrium.

It is a semi-destructive technique requiring prior surface preparation. It is not applicable for measuring σzz and complex shapes. The difference in strain release during the ring-core and hole-drilling method is close to 17%.

Figure 5 shows the comparative results for strain releasing in a sample under observation using slitting, hole drilling, and ring core method. Based on the results, the ring-core method is considered a more accurate and reliable method for residual stress measurement in composite materials.

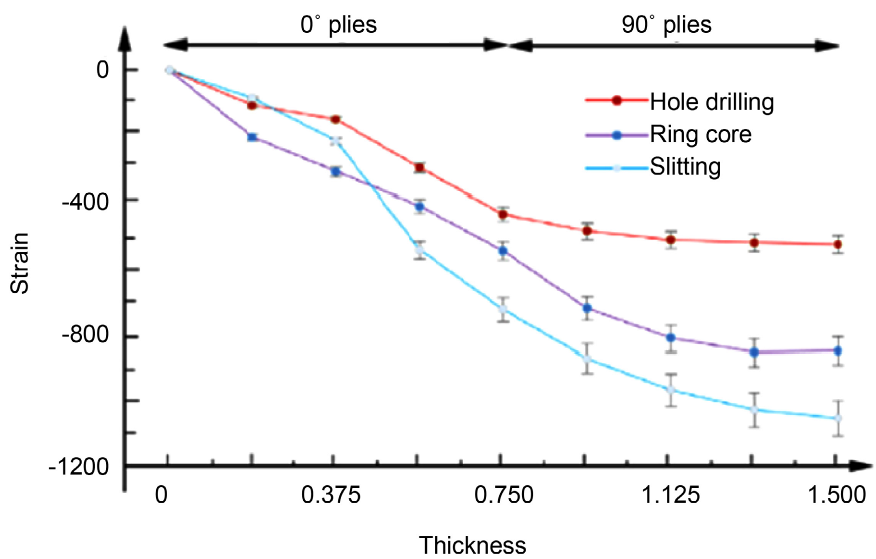

Figure 5. Comparison of released strains in longitudinal direction of laminated composites.

2.1.4. Deep Hole Method

The deep-hole method is a technique that combines the features of both the ring-core method and the hole-drilling, which seems to be a semi-destructive method. DHD method is mostly utilised as a residual stress measurement, particularly in thick metallic components. A reference hole is drilled through metallic thickness, where the diameter of the hole is measured, and eventually, a cylindrical core is trepanned [13]. Moreover, this method can measure assembly stress in AS4/8552 thick composite laminates, whereas DHD method lacks in measuring cure stress in a metal matrix. To relieve the stresses already present in a specimen, firstly a hole is punched in material through its thickness, and afterward, the diameter of the hole is measured. The drill is pinched out from the hole and the diameter of the hole is again measured to calculate the residual stress resulting from changing the diameter of the hole. Measurement of deep internal stresses is carried out via DHD (Deep-hole drilling). **Figure 6** shows the practical steps involved in the deep-hole method for sample drilling.

Deep-hole method is used for measuring the deep interior residual stresses for a large specimen in isotropic materials. The 1D stress profile of components with large thickness is successively measured by the deep-hole method. It is a standard technique for measuring residual stress in aluminium castings and steel (weighing several tons) [11].

The deep-hole method cannot be applied to specimens with thickness larger than 6 mm. It produces semi incursive hole which might need to be filled afterward.

2.2. Non-Destructive Techniques for Measuring Residual Stress

Non-destructive testing is commonly called physical testing because the residual stress of a material is primarily measured using its physical properties. With the development of ultra-precision machining and micro-fabrication technology,

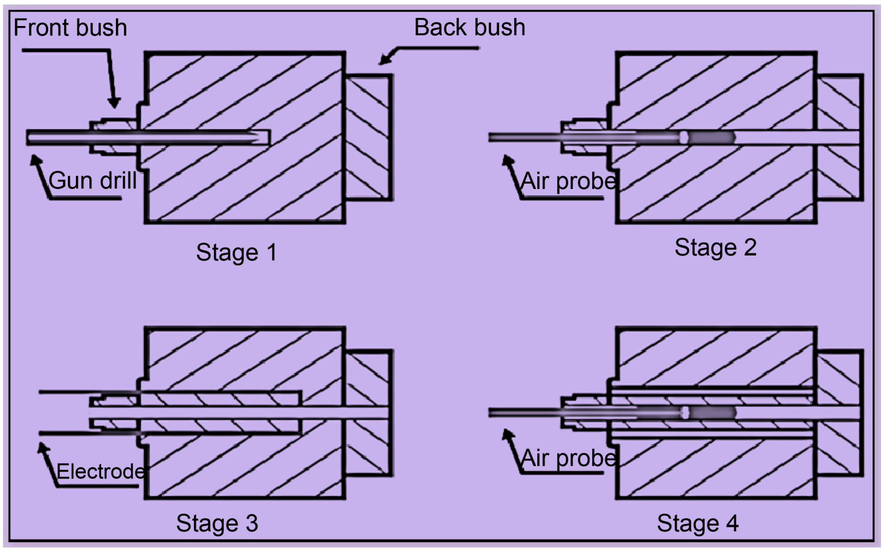

Figure 6. Schematic illustration of DHD.

microstructure residual stress measurement technology has been developed one after another, and the scope of application of non-destructive residual stress tests is expanding. A combination of traditional deep hole drilling and contour technique seems to be a novel approach to measure residual stress through thickness field [14]. *Due to the dynamic advantages of real-time*, non-destructive technology has potential for future development, but due to the short development time, it is not accurate enough at present.

2.2.1. Raman Spectroscopy

Raman spectra are chemical fingerprints that are specific for each molecule or material and can be used to identify a material very quickly and can be used to distinguish it from other materials. Residual stress is measured from the top surface through an average value in the entire interaction volume, thus, can measure stress in transparent through Raman Spectra in various transparent materials. It is conducted in a back-scattering geometry, by which residual stress is mostly distributed in sapphire/Ti6Al4V joint by using non-destructive Raman Spectra [15]. The lattice structure of material changes when stress is applied to it. The interatomic separation of the molecules decreases upon subjecting to compressive stress. Due to the increase in force constant increases oscillation frequency also increases and bands shift to higher frequencies, which is called Raman shift.

In **Figure 7**, Raman frequency shift graph shows how the introduction of residual stress behaves in an unstressed sample. For the unstressed sample, the frequency peak lies at the centre of the graph while compressive residual stress shifts the peak towards right and peak for tensile residual stress lies on the left side of the unstressed frequency curve. Research exhibits that residual stresses are often measured via chemical vapour infiltration (CVI) processes, which are conducted by melting variants of a metal matrix, such as SiC/SiC CMCs [16]. Huang et al. measured SiCf/C/Ti17 composites by using X-ray Diffraction method and Raman spectroscopy. The difference between the measured results from both techniques was within 55 MPa [17], which shows the feasibility of the Raman spectroscopy. Though Raman frequency is widely used to measure residual

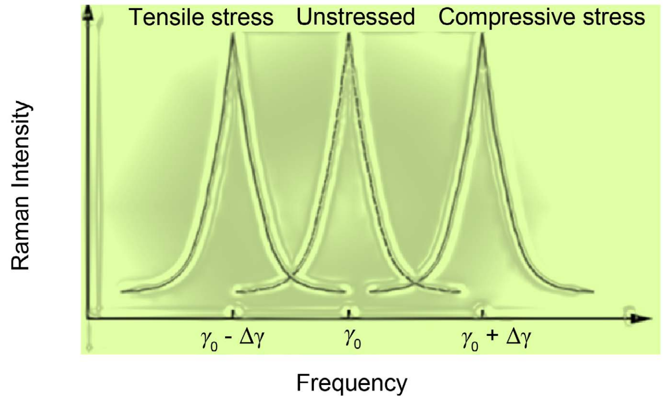

Figure 7. Raman frequency shift phenomenon.

stress accurately, it fails to detect residual strains' levels in composite matrix for its low sensitivity.

2.2.2. Diffraction Techniques

Diffraction methods connect the link between crystallographic parameters that are to be measured and residual stress. It can determine stress value presented in centre points and on top along with lateral surface of cubes developed with the same laser energy [18]. Moreover, optimisation of incremental manufacturing parameters can achieve a proper level of compressive residual stress using 3D methods. Bragg's law is used for measuring elastic strain in diffraction-based techniques [19]. The presence of residual stress in a sample changes the inter-planar spacing (d). Elastic modulus (E) and Poisson's ratio (ν) are accompanied to complement Hooke's Law in the simulation of the residual stress [6]. The measurement accuracy of diffraction technique is still improving to ensure better results.

1) X-Ray Diffraction

No other measuring technique can measure the true residual stress of surface of a material, but X-ray diffraction method measures the strain closest to the surface. The penetration of X-rays ranges up to a tenth of microns, so this technique is liable to subsurface measurement. Here, report unveils how material size distributions along with material-based can be offered by synchrotron X-ray diffraction investigations [20]. It further reflects that diffraction technique enables tessellations to have meshed for finite-element simulations, which widen scopes for evaluation of microstructural effects on properties of material matrix. The penetration of the X-ray beam in a material's sample is dependent on many factors, which are mainly the beam energy and the density of a material. The information obtained in the diffracted beam comes from a volume that is almost 8 to 20 μm below the surface. (The volume of specimen is always slightly larger than the beam size due to scattering of the X-rays by the material) [21]. In an X-ray technique strain within the space, a lattice is measured and residual stress produced by that strain is calculated considering linear elastic distortion of the crystal.

X-ray technology is used for measuring subsurface residual stress in aluminium, titanium, and other alloys. It measures high magnitude of biaxial micro and macro residual stresses accurately and has no limitation on shape geometry. The nominal accuracy of this technique is 7 MPa—Aluminium, 20 MPa—Steel, 10 MPa—Titanium.

X-ray diffraction technique is only applicable to polycrystalline material and is highly affected by grain size and texture. Internal surfaces of materials are not measurable without some prior cutting (and consequent relaxation) of the specimen because X-ray diffraction is limited by the requirement for line-of-sight access.

Figure 8 shows the quantitative results of longitudinal residual stress in the depth of the sample caused by shot peening in a sample using X-ray and centre-hole drilling techniques. It shows centre-hole drilling provides detailed but

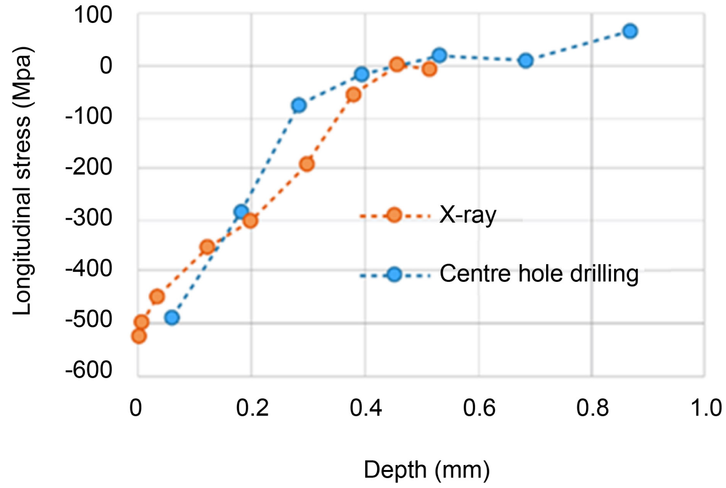

Figure 8. Shot peening residual stress.

less precise results.

2) Neutron Diffraction

In neutron diffraction, by detecting the diffractions of an incident electron beam residual stress can be measured deep within a material. This phenomenon is known as Bragg's Law which is since stress within a material changes its atomic lattice spacing which is detected by the diffracted beam of neutrons.

Figure 9 illustrates how the incident beam falls on the plane having residual stress in it and lattice spacing changes accordingly. To calculate the absolute stress values, calculations are carried out in a stress-free material specimen (*i.e.* d0 sample) and then the relative changes in spacing are then marked.

$$n\lambda = 2d\sin\theta \tag{1}$$

where Δd is the change in lattice spacing, d_0 is the lattice spacing, $\Delta\theta$ is the peak shift, and 2θ is the corresponding diffracted angular position in the stress-free sample [22].

The depth of penetration for a neutron beam is of few centimetres so it is used for measuring the residual strain in volume of a sample.

The neutron diffraction method is a powerful technique for measurement of residual stress because it had very high spatial resolution [23]. It can be utilized to obtain a complete 3D map of the residual stresses within a specimen. Deep penetrating effect of neutron beam can be therefore used for acquiring data from large assemblies or intact parts, which can be placed in service or afterward can be re-evaluated. For inaccuracies of stress approximation, there is minimal need for cutting up specimens.

For measuring internal stresses due to their deeper penetration into engineering materials, neutron diffraction is the most used technique. Neutron diffraction can well distinguish between all three types of residual stress. σI is detected by peak shift while broadening of line detects σII and σIII. A high magnitude of tri-axial micro and macro residual stress is measured including stress gradients.

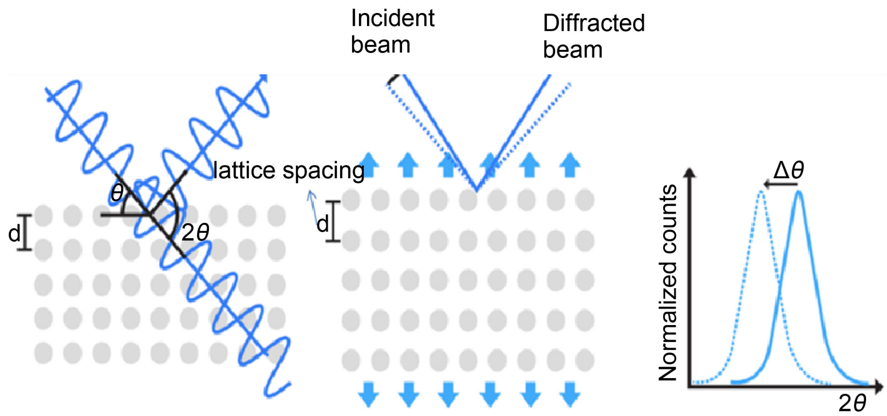

Figure 9. Incident and diffracted beam with varying lattice spacing.

The nominal accuracy of ND is 10 MPa—Aluminium, 30 MPa—Steel, 15 MPa—Titanium [24].

It applies only to crystalline material and is highly affected by grain size. Larger and thick components are not likely to be accurately measured by neutron diffraction.

2.2.3. Indentation Technique

"Hardness of a material depends on the stress acting on it" this fact leads to the development of hardness measurement method. These techniques *i.e.* Rockwell hardness test, Knoop Test, and Brinell hardness test are used for residual stress determination. Investigations of steel samples unveil in-situ applicability along with nano-to-macro ranges of evaluation, which reflects the ability of indentation technique. In this context, the application of Lee's model is reported for a state of non-equibiaxial residual stresses [25]. The accuracy of stress measurement based on hardness techniques depends on a lot of parameters. The schematic illustration of indentation technique is shown in **Figure 10**. It shows how the application of force penetrates the depth of the sample.

Recently, indentation methods with the combination of FEM have become a hot research area. Hao *et al.* studied the effect of the dimensions on the indentation method by the finite element method and estimated the residual stresses corresponding to different indentation depths based on the Suresh model [26]. When the results were compared with those of the residual stresses in given states, the reasonable indentation depths for the measurement of the biaxial tensile and compressive residual stresses in a 2A12 aluminiumalloy were 0.65 mm and 0.45 mm, respectively, as shown in **Figure 11**.

This technique is non-destructive and applicable for materials whose initial hardness value is known and then change is measured. It is recently used for residual stress measurement in biological tissues and metallic alloys.

2.2.4. Ultrasonic Testing

The ultrasonic stress measurement method is based on acoustic-elasticity effect "the velocity of elastic wave propagation in solids is dependent on the mechanical

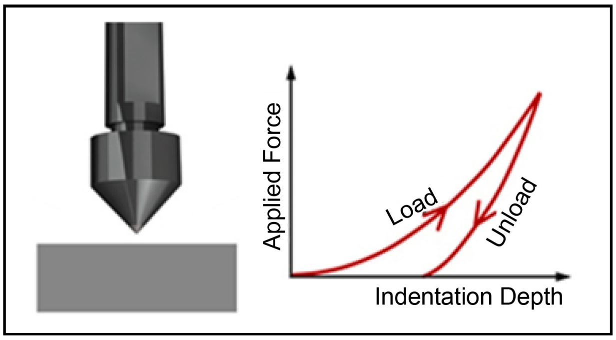

Figure 10. Schematic of Indentation testing method.

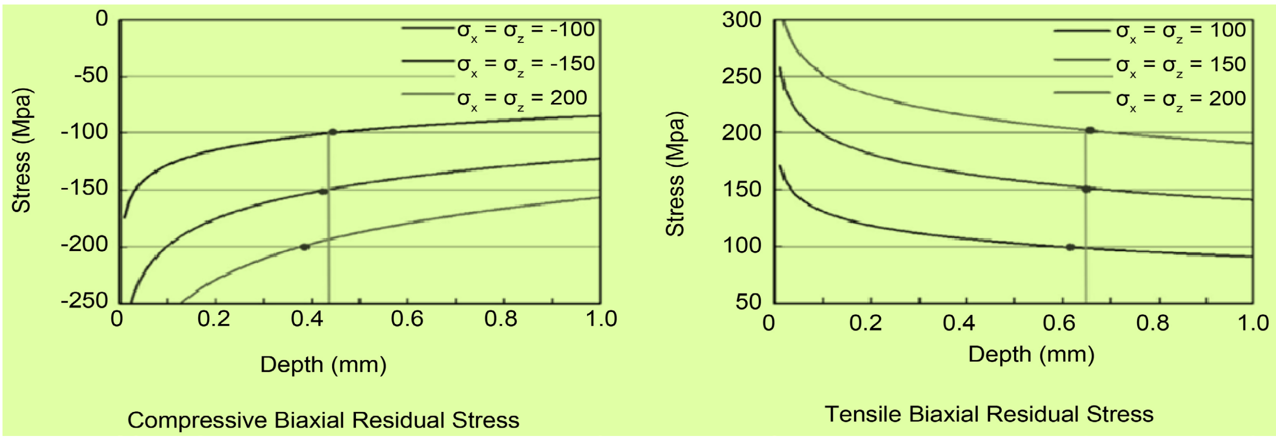

Figure 11. Estimated and true residual stress values at different depths for 2Al2 aluminum alloy

stress". Ultrasonic techniques can detect all kinds of residual stress but unable to differentiate them. There exists a linear relationship between the residual stress of material and the wave velocity.

$$V = V_o + K_o \tag{2}$$

Figure 12 shows the schematic of snell's law (serves as basis of ultrasonic method). The ultrasonic testing method can integrate distinct configurations, which are intended to alleviate residual stresses from metal components and matrices. The use of this technique requires a transmitting transducer, which introduces waves that can be propagated through material components with effective detection. The same transducer is used for excitation and receiving of ultrasonic waves in pulse-echo method [27]. Magnetostrictive effect is the basis of the magnetic strain technique according to which upon magnetization, size of ferromagnetic materials got changed. Material permeability changes when stress is applied to the ferromagnetic material. This amount of applied stress is proportional to permeability change. The residual stress is determined by measuring the change in magnetic resistance in the circuit by calculating the amount of current [21].

For analysis of internal residual stress ultrasonic technique is effective. The depth profile obtained by ultrasonic method is much greater than X-ray technique. Emergence of residual stress can drastically limit manufacturing components' rapid development and feasibility [28]. Laser ultrasonic technology is

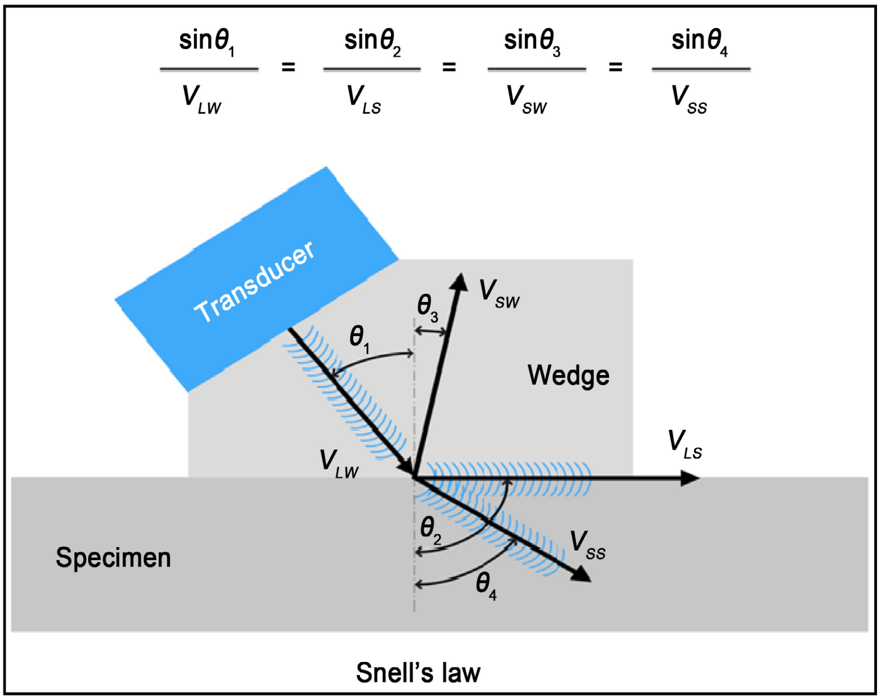

Figure 12. Schematic of snell's law. where, VSw: shear velocity of the wedge; VLw: longitudinal velocity of the wedge; Vss: shear velocity of the sample; VLs: longitudinal velocity of the sample.

advanced non-destructive testing that can effectively measure residual stress, such as in TC4 titanium alloy. Ultrasonic technique is free from hazard materials, portable, inexpensive, and easily used for large industrial components *i.e.* steam turbines and discs etc. However, some limitations are also noticed, as ultrasonic traducers are restricted to smaller depths, and further fail to differentiatemulti-axial stresses' effects.

3. FEM Validation

In order to verify the accuracy of measurement, experimental detection and simulation methods are generally combined. A validated model is utilised to explore distinct pre-heating techniques as well as probable strategies to avoid final distortions brought forward by residual stresses [29]. Thermo-mechanical issues presented in numerical simulations can also be alleviated by characterising mechanical behaviour in a metal matrix. For finite element models validation, biaxial data from X-ray diffraction, biaxial data from Hole-drilling, and tri-axial data from the neutron beam can give a coherent picture of stress distribution [30].

In this regard, an overlap of neutron data can be noticed by data of hole drilling with the effect of biaxial assumption in a tri-axial region will be observable. Laser-based welding procedures can incorporate Cold Wire Assisted Laser Welding (CWLAW), Autogenous Laser Welding (ALW), and Hybrid Laser-Arc Welding [31]. Three dimensional, such as thermo-metallurgical-mechanical finite processes can mitigate residual stress in material components. These have included various strain gauge cut-ups, imaging with various chemical etching techniques, micro-hardness mapping, saw-cut surface studies, and many other approaches [32].

4. Numerical Analysis and Experimental Studies on the Residual Stress

ABAQUS software is used for carrying out experimental measurements and numerical analysis of W/2024Al composites in which residual stress is induced by quenching. Assessment or measurement of residual stresses can be achieved by using a finite element method (FEM) that is in as-quenched composite blocks. A further emphasis mirrors how experimental residual stress measurements on external surfaces of the welded model can be conducted by using an X-ray diffraction technique [33]. It is reliable due to the accurate calculation of heat transfer coefficients and the established constitutive equation for the description of the variation of yield stress at elevated temperature with different strain rates. To validate the simulation results, X-ray diffraction and crack-compliance methods were carried out to measure the stresses that developed at the surface and interior of the composites [34]. The influence of temperature on quenching medium is taken into consideration for investigation of residual stress induced in quenched composite blocks. Therefore, it can be easily concluded that a single technique is not reliable for accurate measurement, for full-field internal and external measurement of residual stress different techniques are required to complement the accuracy of data .

5. Example of Applying Multiple Technqiues for Improving Accuracy of Residual Stress

To induce multiaxial residual stress, the disks of aluminum alloy were deformed plastically. The residual stress on surface is calculated by contour method. The disc was afterwards cut in two halves, one half is examined via hole drillng and residual stress in opther half is measured by X-ray technqiue [35]. Diffraction measurements are taken on an uncut disk. The measured surface stress is superimposed with with the calculated internal stress relaxation, and gets an original, internal stresses value which is then compared with neutron diffraction measurements for uncertainity check. Contrarily, magnetic estimation in welding activities is noticed to use mechanical tensile testing resulting in failure of welding [36]. Thus, strategic choice of multiple techniques can be conducive to alleviating residual stress to ensure accuracy. Using multiple technqiues theory help in measurements of residual stress in in parts where it was difficult to access the interal stresses.

6. Results and Discussion

Finally, the following points should be kept in mind while choosing the most appropriate technique for measurement of residual stress.

7. Conclusion

There is a wide variety of methods for measuring residual stress in different states and for different situations. This study has shed light on how mechanical methods in measuring residual stress in metal matrices can deliver positive outcomes regarding reducing vulnerability of materials. Nevertheless, contrary observations have also revealed their failure to measure cure stress. This is where importance of implicating new techniques comes forth, such as magnetic, ultrasonic, and other methods. The specifications and circumstances of the component should be thoroughly considered while choosing an experimental approach for practical simulation of residual stress, such as field feasibility and adaptability, accuracy, resolution, expenses and efficiency.

8. Future Prospects

With the advent of the latest techniques, measurement methodologies are shifting primarily to non-destructive testing techniques to avoid minimal to no harm to the specimen. All measurement techniques have inherent flaws in one way or the other [26]. At present, it cannot be concluded that one fix technique is perfect in all manners. So, we must choose the measurement technique depending on material properties, accuracy, and situation. Additional information and data can be obtained by combining both destructive and non-destructive techniques so the accuracy of residual stress evaluation from mechanical release measurements can be improved. Multiple approaches are combined to solve problems that cannot be solved within the scope of single technique. Observing cracks and characterizing them is difficult. For example, quantitative characterization of cracks by a combination of acoustic or optical measurement techniques would be a new track for the measurement of residual stresses quantitatively using chemical means. Optical measurements are well applied for strain measurements. Combining the optical method and ring core technique can lead to more accuracy of measurements. In the same way, by combining ultrasonic and magnetic methods irrespective of the similarity between these two techniques, changes in shear wave reflection amplitude can be measured at varying excitation intensities using ultrasonic signals. Besides these other magnetic properties such as increased permeability and coercive force can also be used for taking measurements. There is still room for development in the direction of this research, and it is important to correlate the advantages of each technique and minimize the disadvantages to ultimately obtain very accurate and precise data.

Along with the ability to display stress distributions, there is an increasing demand for quantification and direct visualization of residual stress fields at the micro/Nanoscale. The current measurement techniques lack in measuring uniform stress over the whole field, although finite element analysis is used for full-field measurement it involves too much error and uncertainty. Future measurement methods for residual stress are expected to consider residual stress on a whole dimensional plane combining artificial intelligence to make measurement more precise. It is an indispensable direction for research in the field of residual stress measurement.

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Data Availability Statement

Some or all data generated or used during the study are available from the corresponding author by request.

Conflicts of Interest

There are no conflicts to declare.

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