Residual stress measurement techniques: A review

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ABSTRACT

KEYWORDS

Residual Stress,
Destructive,
Non-destructive.

Material surface integrity enhancement has been a trending topic in the recent years. The major factors such as surface roughness, hardness, microstructure and residual stresses are essential for surface integrity studies. Among all these factors, residual stresses are gaining more interest due to their complexity and no clarity over the precision of their measurement methods. Residual stresses are complex and can hugely affect the material due to their tensile – compressive nature. For instance, tensile residual stresses can harm the material performance, while compressive residual stresses can improve it. Therefore, it is very important to analyse these stresses and in the past decade, there has been significant progress in their measurement methods. This paper attempts to present a detailed review on various residual stress measurement methods that are in practice and provide an overview of the advancements in this area. Each method is presented, analysed and discussed in this review.

1. Introduction

Residual stresses are the stresses that stay in a component after removing the original cause of the stresses Wikipedia (n.d) or in other words, they are the stresses present in the component structure that are independent of external loads. Residual stresses are identified as one of the main factors affecting the component properties, which may affect the performance of the component (Guo, 2020). To be specific, residual stresses are observed to have impact on fatigue strength, corrosion strength, structural strength etc., so are ultimately affecting the life of the component. Their effects are not noticeable easily but can be slowly observed during the component's service life. The general understanding of the residual stress is that; they are unavoidable and may either be useful or not useful. For example, a decreased tensile residual stress or an increased compressive residual stress improves the fatigue strength of the material. In simple words, tension causes the increase in length of the object; and compression results in decrease in length. Most of the manufacturing processes – grinding, heat-treating, machining, metal forming etc. produces residual stresses. Depending on the type and nature of residual stress, there are methods to intentionally introduce them into the components using techniques such as peening; or even remove the existing ones in the components using stress-relieving techniques such as heat-treating, cryogenic treating etc.

From all these observations regarding the nature and effects of residual stresses, it is worth stating that their measurement is an absolute necessity and it is the responsibility of the researchers and practitioners to measure them accurately in order to identify the harmful as well as useful effects of these stresses to either avoid them or make the best use of them. There are several methods to measure residual stresses and can generally be classified as destructive and non-destructive methods. In the past few years, there has been attempts to identify the best method for residual stress measurement, which is precise as well as economical. Table 1 shows the most commonly practiced methods for measuring the residual stresses. The selection of the method relies on several factors such as location selection for testing (Ex: on surface or subsurface of test specimen), nature and depth of the testing penetration, composition-geometry of the test specimen, measurement precision scale requirement (micro, macro, meso) and environmental requirements etc. With background from this section, the subsequent sections will review about all the residual stress measurement methods that are listed in Table 1, and discuss issues related to their application and implementation through a detailed literature review.

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2. Classification of measuring methods

The destructive measurement methods involve the removal of material in order to test the work specimen, and the stress is measured with respect to the displacement or strain occurring during the removal. As shown in Table 1, drill hole, ESPI, ring core, contour, crack compliance and stripping methods are categorized as destructive (fully or semi destructive) measurement methods. Over the years, destructive methods have transitioned from surface stress measurements to internal stress measurements due to its effectiveness. On the other hand, non-destructive measurement methods involve physical testing for measuring the stress related parameters and later analysing them with respect to their material physical properties. Non-destructive measurement methods involve diffraction (x-ray, neutron and synchrotron), magnetic, ultrasonic, nano indentation and Raman spectroscopy methods. The various methods are presented, analysed and discussed below.

2.1 Hole drilling method

Strain Gauge: Hole drilling method using strain gauge is recognized as a semi-destructive method for residual stress measurement. They are advantageous due to their ability to produce high precision measurements and being relatively simple, inexpensive and quick in comparison to other measurement methods that are in practice. They have standard test procedures and can easily be implemented, which makes them popular among all methods. Generally, the procedure involves penetrating the work specimen surface in the form of a small sized hole (Fig.1). Test specimens are prepared with care by avoiding processes such as abrading or grinding, which has the tendency to corrupt the results (Slideshare.net, 2020). After identifying and selecting the test location on the sample surface, strain gauge rosettes are installed concentrically around the hole. The gauges are connected to a static strain indicator capable of reading micro measurements. The results are gathered in the form of strain, which is caused by the drilling action. From these measured strain values, the residual stresses are evaluated by using the equation and constants relevant to the type of rosettes and setup used. The minimum depth of the hole is restricted to 0.5 times the hole diameter (Rossini et al., 2012). The test procedure has been standardized and proper guidelines are presented in ASTM standard test method E 837 (Slideshare.net, 2020; Guo et al., 2015).

Table 1
Residual stress measurement methods.

Destructive methods	
Hole drilling method	Strain gauge
	Electronic Speckle Pattern Interferometry (ESPI)
Ring core method	
Stripping method	
Crack compliance method	
Contour method	
Non-destructive methods	
Diffraction method	X-ray
	Neutron ray
	Synchrotron radiation
Magnetic method	Magnetic strain
	Magnetic memory
	Magnetic noise
	Magnetomechanical acoustic emission
Nano indentation method	
Ultrasonic method	
Raman spectroscopy	

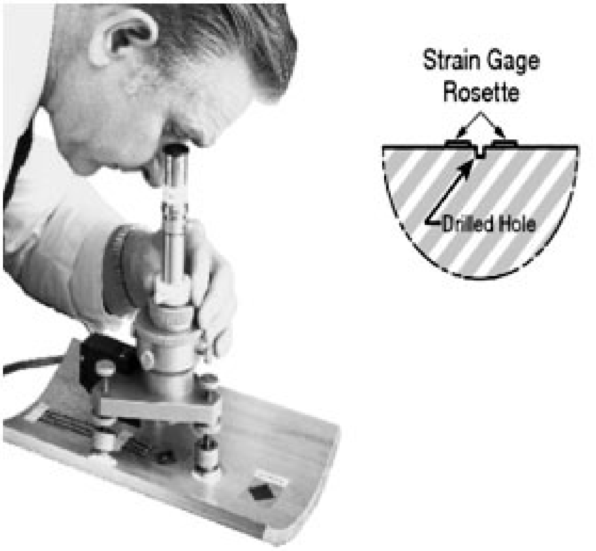

Fig. 1. Hole drilling method.

This makes the hole drilling method one of the easiest method, which can be performed by anyone with minimal training. This method is also flexible with options to perform indoors as well as in the field (outdoors) on objects of various sizes and shapes. The destruction caused by this method is considered as minimal as the size of the hole is small causing minimal harm to the surface integrity of the tested objects (Vishaypg.com, 2020). However, it is worth mentioning that this process has few vulnerabilities. The drilling of hole needs to be carried out precisely in order to avoid possible errors such as – irregularity in shape of the hole, eccentricity, residual stress getting mixed with machining stresses etc.

This method introduces additional errors due to the sticking nature of strain gauge rosette used. The precision of the method is influenced by the calibration coefficients. The calibration of the stress release coefficients is now a days defined using FEM techniques, due to their convenience but their accuracy in terms of validating the calibration coefficient still needs to be further studied and justified (Guo et al., 2019). Valente et al. (2005) performed experimental and numerical analysis to validate the residual stress fields in plasma sprayed ceramic deposited on metal substrates using hole drilling and finite element methods. Finite element model was used to determine the calibration coefficients, which are required for the residual stress calculation. The FEM model proved to be successful in determining the precise values. They also analysed the influence of eccentricities of drilled hole causing possible errors in measurements and the effect of low thermal conductivity on drilling process and finally proposed a calculation method in order to identify the correct experimental conditions. Kim et al. (2007) in their investigation tried to compare the incremental hole drilling method with layer removal method for measuring residual stresses in injection molded polymeric part. Experimental results were compared with predicted numerical analysis using Moldflow software. In comparison they found the hole drilling method as efficient and could be used for injection molded parts and any complex shapes of polymeric parts. They observed the additional stresses causing errors during residual stress measurement process and suggested the need for extra attention on the process environment in order to improve the precision. Qin et al. (2014) have proposed the combination of hole drilling method and Moire interferometry to determine the testing area for reduced errors. With their findings and comparisons between theoretical and experimental results, they were able to determine the measurement area with least error possibilities. Nagy et al. (2017) have tested the incremental drill hole method for residual stress measurement on welding. They prepared the setup for stiffener-to-deck plate connection of an orthotropic steel deck and optimized the test procedure in order to minimize error occurrence during measurement. They identified that sample surface preparation and the precision of the zero depth setting are most influential in avoiding errors, and took necessary steps in order to avoid it. With the help of proper grinding and visual inspection tools, they precisely measured the patterns of tensile residual stresses near the weld area. Magnier et al. (2018) have tried to broaden the application of hole drilling method by testing them on thin components. They determined the calibration coefficients using finite element method for metal sheets of thicknesses 0.7, 1.0 and 1.6 mm and measured the residual stress using incremental drill. They validated the results and found them accurate up to half of the sheet thickness.

Electronic Speckle Pattern Interferometry (ESPI): This method came into existence due to the issues with strain gauge measurement in accuracies in hole drilling method. When researchers identified the strain gauge being the main factor causing errors, a new method (ESPI) was proposed which uses light as an alternative to strain gauges in hole drilling method in order to improve the precision and also makes the measurement process faster. The setup of method includes- test object, laser emitter, beam splitter, zoom lens, piezoelectric transducer, phase stepper, fiber optics, charge coupled device (CCD) and computer as shown (Fig. 2).

The process starts with sending of laser beam from the emitter, which is split into two, while passing through the splitter. One of these beams strikes the test object surface and its speckle pattern is obtained in the zoom lens. The other beam from the splitter passes through the piezoelectric transducer controlled by the phase stepper, and then formed in the lens through fiber optics. All these information are recorded by the CCD, which is then transferred to a computer to analyse the patterns in order to determine the strain. This displacement measurement method has proved to be more precise compared to the traditional strain gauge hole drilling method due to its non-contact nature (Guo et al., 2019). Over the years, there have been several attempts to make this process more

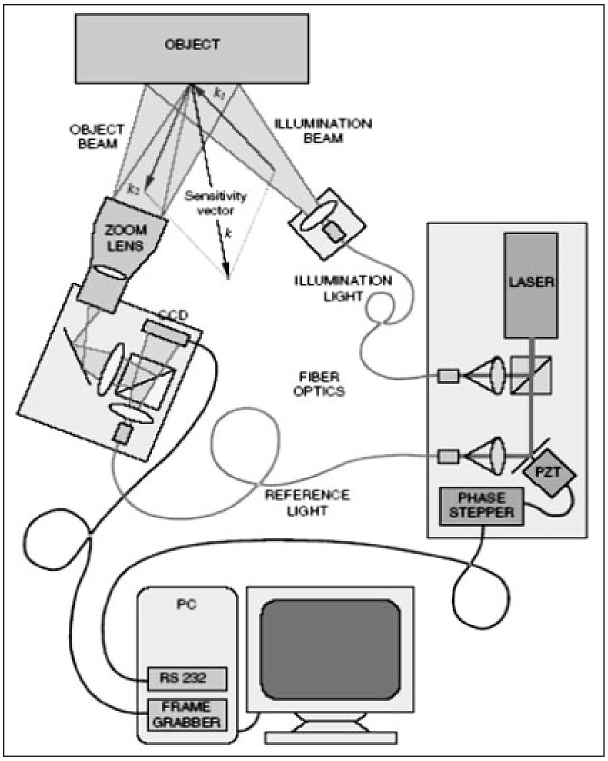

Fig. 2. ESPI setup (Prime & Hill, 2006).

precise. Barile et al. (2014) have worked on the drilling process parameters to improve the residual stress measurement process by using hole drilling method with ESPI. Titanium plates (Ti6Al4V) are the material tested for the drilling speeds ranging from 5000 rpm – 50000 rpm, and the best results in terms of drill hole quality and minimized irregularities were observed at the highest cutting speed. Rickert (2016) tested the precision of hole drilling-ESPI method by testing it on different materials. Aluminium alloy 7075, tool steel O1 and polycarbonate were the materials tested and the author observed the irregularity in measurements due to the microstructural variation caused by the drilling process. Among the three materials tested, the hole drilling-ESPI method proved to be more precise in the case of aluminium alloy 7075.

2.2 Ring core method

Ring core method is similar to hole drilling method with slight variation in the technique. Similar to hole drilling method, the ring core method uses the stress release during material removal and the difference between the ring core and hole drilling method is the measurement location, as the hole drilling method measures the values in the surrounding area, whereas the ring core uses the centre area. The material is cut using a cutter in the form of groove at the targeted location and the rosette strain gauge is attached in the middle of the ring core area. The measured values from the strain gauges are then used in the equation for residual stress, which is similar to the hole drilling method. The ring core method is advantageous in terms of producing more accurate measurement values, which is due to the reason that this method can produce much larger strains in comparison to hole drilling method. However, it is also disadvantageous due to the damage it is causing to the test specimen, which is a great concern for the researchers while testing rare and expensive materials. Vaclavik et al. (2010) have investigated the ring core method using experiments and FEM simulations. The relaxation coefficients are derived from FEM model. After comparing the sensitivity with hole drilling method, they identified the ring core method being more suitable for measurement of under surface stresses. Song et al. (2011) in their study used Focussed Ion Beam (FIB) to introduce the strain relief by ring core milling on thin films. Trench cutting is the method used to evaluate the residual stress, by recording the images of strain changes and later by using Digital Image Correlation (DIC) micrograph analysis. Experimental results were compared with FEM simulation and they found good agreement between them. From their findings, they concluded that the FIB – Ring core method with a proposed empirical mathematical description in terms of strain relief master curve function could be more efficient at the micron to sub-micron level of stress evaluation. Salvati et al. (2016) have investigated the effect of materials anisotropy on the precision of residual stress evaluation. FIB-DIC ring core is the method used to investigate the uncertainty in stress evaluation due to unknown orientation of material. Micron scale analysis was performed and the statistical analysis showed that widest range of stress values are obtained, when strain is uniaxial and the material with the highest anisotropy IN 718 produces the broader distribution of possible stresses.

2.3 Stripping method

This method is one of the well-known method to measure the residual stress inside the specimen and has been categorized as a fully destructive method. In this method, the material is removed in the form of layers and the deformation is observed. The method uses the theory of elasticity and also assumes that the residual stresses in each layer is distributed uniformly. The layer removal can be performed either by milling or chemically by electrolysis. Since the stress, measurement is completely dependent on the depth of the removed layer, this method is compatible for flat and cylindrical shaped specimens. This method faces several issues such as low accuracy, fully destructive etc. The accuracy is affected because it uses the method of averaging the stress values, which may not be good enough for certain applications (ex: welded parts). Introduction of the stresses during the process is one of the technique in practice to minimize the errors. This method also faces issues such as non-uniformity of the material removal process, which could only be solved using optimal machining conditions. Many of these issues are solved in the contour and crack-compliance methods. Ekmekci et al. (2004) have investigated the nonlinear material removal characteristics by testing the stripping method on electrical discharge machined (EDM) surface. Electrochemical polishing is the method used to remove the material. During layer removal process, variation in voltage with respect to time was clearly visible, which had started after the steadiness of the first few removed layers. Stripping method is based on the assumption of linear material removal rate and the authors stated that the non-linearity behaviour observed in their tested specimen could affect the accuracy of measurement process due to inaccurate measured thickness values. Schongrunder et al. (2014) used a new approach by using ion beam layer removal (ILR) method to determine the stresses on thin films. An analytical Euler – Bernoulli beam theorem has been compared with finite element simulation to measure and analyse the stress profile in a thin tungsten and titanium nitride film deposited on a single crystalline silicon wafer. By considering the cantilever geometrical variation due to manufacturing, various boundary conditions and relaxations during cantilever fabrication are applied. They observed that the boundary conditions and cantilever fabrication a most influential in stress distribution in the case of thin films.

2.4 Crack-compliance method

The crack-compliance method is based on the analysis of cracks in linear elastic materials. This method involves the removal of material in the form of small slots to observe the stress relaxation at the surroundings of the crack (Fig. 3). By slowly increasing the slot depth, the stress field normal to the crack is resolved as a function of depth (Tolstikhin, 2017). The method is considered as simple and economical but is not suitable for complex structures and high stress amplitudes. Nervi and Szabo (2007) have investigated the errors in residual stress measurements associated with crack compliance method. They have identified the mathematical model used for interpretation of experimental values and the errors in the numerical solutions obtained and observed that these are the main factors affecting the accuracy of this method.The authors stated that the mathematical model in practice is flawed, due to its assumption of generalized plane strain conditions being existed in the plane of symmetry. They also stated that this assumption would only work, if the dimension of the test sample perpendicular to the symmetry plane would be much larger than the other dimensions and majority of samples do not satisfy this condition. Dong et al. (2015) in their study compared the crack compliance method with the x-ray diffraction method for residual stress measurement. Al-Cu forged blocks that have gone through quenching and aging, is the tested material in their study. Evolution of residual stress during quenching was simulated using a zone based heat transfer calculation combined with hyperbolic sine-type material constitutive model. Whereas, residual stress relaxation during aging is simulated using Norton creep law. Numerical simulations results were compared with the experimental results and there was good agreement between them. They observed reduced residual stress with respect to decreased cooling rate during quenching and similar in the case of aging treatment.

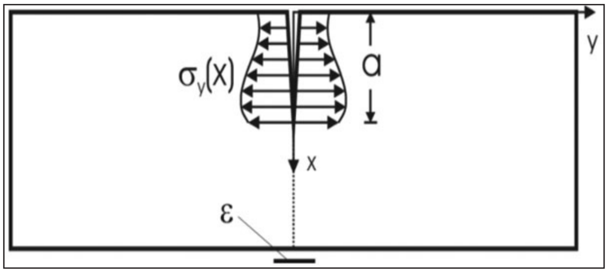

Fig. 3. Crack compliance method (Javadi et al., 2017).

2.5 Contour method

The contour method is a newly developed method, which is based on Bueckners elastic superposition principle. This method is an invention of early 21st century and was developed to overcome the flaws in other destructive methods, such as stripping method and crack compliance method. After being tested, validated, and over

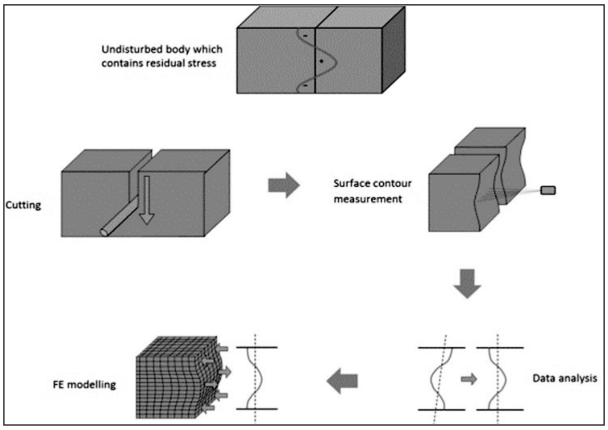

Fig. 4. Contour method (Nanai et al., 2020).

a decade of research and developments, the contour method is finally being recognized as one of the most feasible method with high accuracy for measuring residual stresses in welding. Generally, it is a relaxation method that activates a two dimensional residual stress map, which needs to be analysed on a plane. The process involves cutting the test specimen containing an unknown residual stress as shown in Fig. 4. Cutting surface is deformed and some stress is released after cutting. In order to reform the shape of the cut surface an external stress is applied on it, which is also referred to as the residual stress. In practical applications, a finite element model of the cut specimen is used to evaluate the stress distribution pattern. This method provides high resolution and requires no calculation, but the FEM model preparation and data acquisition needs to be extremely precise in order to achieve high accuracy results. Pagliaro et al. (2010) have tried to improve the limitations of this method by trying multiple cuts on a single test specimen. They tested this theory by conducting experimental investigations on 316L stainless steel disk and by validating the finite element model results with neutron diffraction method results. They found the multiple cut contour method in good agreement with the neutron diffraction results, with slight root-mean-square deviation of 28 MPa – 34 MPa. Vrancken et al. (2014) have investigated the effect of residual stresses on the mechanical properties of the selective laser melting (SLM) treated test specimens. Ti6Al4V specimen produced by SLM is the material tested using the contour method. The 2-D stress mapshowed the effect of residual stress on the anisotropic nature of the test specimen. Fracture toughness test and fatigue crack growth test indicated the highimpact of residual stresses on the fracture behaviour of the tested material. Olson et al. (2015) have investigated the measurement uncertainty in the contour method. They identified that the cause of errors are due to the noise during the process and the smoothing of surfaces. From the numerical and experimental study on quenched aluminium, with the use of single measurement uncertainty estimator, they observed higher uncertainty near the perimeter of the measured plane. Ahmad et al. (2018) have tested the contour method on Ti6Al4V and Inconel 718 samples produced from SLM. Inherent strain based numerical simulation method is compared with the experimental results and found to be effective. They observed the compressive stress at the centre and tensile stress at the surface.

2.6 Diffraction method

Non-destructive methods are popular due to their least material damage nature and the diffraction method is classified as one of the most popular and well sorted non-destructive testing method (Guo, 2020). Diffraction methods are fast, taking only seconds to few minutes for measurement (Guo et al., 2015). There are 3 types of diffraction methods – X-ray, neutron ray and synchrotron. Diffraction method is based on assessing changes in the inter planar spacing, which is caused by the elastic deformation, by measuring the elastic strain using Bragg's law and stresses are calculated using Hooke's law. During testing, initially the material in the powder form with no stress is measured in order to set the detector's angular scale to that material. Stress is then measured from the slope of graph obtained from the lattice distance w.r.t. various tilt angles. In X-ray diffraction, when a solid specimen is exposed to stress, the atomic planes in the metallic crystal structure changes due to the experienced strain. This atomic spacing is measured and stress is evaluated using them. This method is well suited for crystalline materials. Their high accuracy makes them one of the most widely used methods among all. ASTM E2860 - 12, ASTM E915 - 16, ASTM E1426 - 14, BS EN 15305:2008 are the few recognized standards for XRD method usage. In an attempt to improve the accuracy of XRD, Guo et al. (2015) have developed and tested a polycapillary X-ray optics in their study. From their experiments and comparison with the traditional pinhole method, they observed great level of accuracy and an extended testing range provided by the Slightly Focussing Capillary X-ray Lens (SFCXRL). Similar to X-ray diffraction, Neutron diffraction is also based on Bragg's law and Hooke's law. They are well suited for thick components with ability to measure stresses to a higher depth (Guo et al., 2015). ISO/TS 21432:2005 is the recognized available standard for their usage. However, they are not widely used due to their limited availability, highly expensive and mediocre spatial resolution (in mm's). Karpov et al. (2020) have tested the neutron diffraction method using a STRESS neutron diffractometer. The presence of residual stress in parts produced by direct laser metal deposition (DLMD) additive manufacturing technique is analysed for metal plates of AISI 410 and Inconel 625 materials. Their investigation showed good results in terms of identifying the difference in stress distribution in the substrate of the samples. Synchrotron radiation diffraction method uses higher energy to produce a higher resolution stress measurement. They do have the ability to measure stresses in complex structures and to a larger depth (Guo et al., 2015). However, their usage is restricted to common practice due to safety concerns, so are available in only few facilities.

2.7 Ultrasonic method

Application of ultrasound has shown most promising results in the category of non-destructive residual stress measurement methods. This method works based on the acoustic-elasticity effect, according to which the residual stress is measured using the propagation velocity of an ultrasonic wave caused by the stress in the test specimen. The procedure starts with sending ultrasonic waves to test specimen using a transmitter device. These propagated waves are then detected and received by a receiver device or in some cases a single transducer is capable of both transmitting and receiving waves. Ultrasonic method is advantageous due to its applicability on thicker and larger components or any type of materials. Other than its convenience they are also flexible, safe and less expensive compared to other non-destructive methods. Javadi et al. (2013) have investigated the limitations of ultrasonic method by testing it on steel plates to measure the welding residual stresses. Stress measurements are made using different frequency waves (1 MHz – 5 MHz range). From the validated results of 3D FEM analysis and hole drilling method, the authors proposed a combined Finite Element – Longitudinal Critically Refracted (FELCR) method for effectiveness in welding residual stress measurements. Xiu et al. (2018) have tested the trailing welding ultrasonic impact treatment to redistribute the residual stress on vacuum vessels that are welded by a narrow gap TIG welding. A numerical analysis is also performed using ABAQUS software to obtain the optimal treatment parameters to remove the welding residual stresses. Parameters such as impact method, impact pin diameter and the impact frequency are investigated and the results showed the reduction in residual stress due to the tested treatment. The results also showed the ability of the trailing welding ultrasonic impact treatment in terms of changing the residual stresses from tensile state to compressive state.

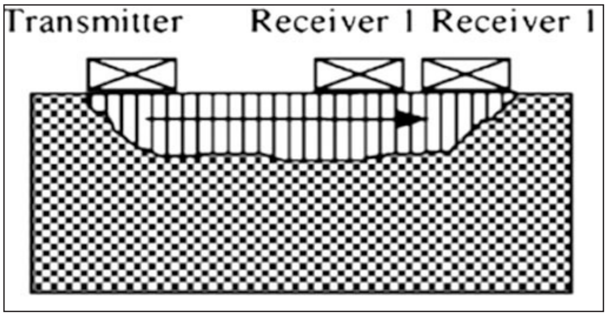

Fig. 5. Ultrasonic method setup (Rossini et al., 2012).

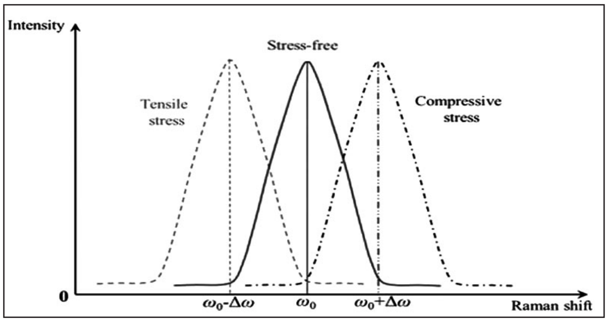

Fig. 6. Raman spectroscopy measurement (Qu et al., 2019).

2.8 Raman spectroscopy

Raman spectroscopy is an analytical method, which is based on the deviation in frequency or wave number during light scattering. The deviation is observed in the Raman spectrum, when band shifts to higher frequencies which is named as Raman shift as shown in Fig. 6. It is a non-destructive method, capable of measuring non-uniform stresses. However, their accuracy is a question mark for the researchers, as it is highly vulnerable to factors such as room temperature, focussing inaccuracies, poor quality data recording etc. There have been many attempts to ultilize this method accurately in the measurement of residual stresses. Qiu et al. (2016) have proposed a methodology to measure the residual stresses induced in Si-based multilayer heterostructures. The methodology consisted of a combined experimental and theoretical approach that involve the usage of scanning electron microscopy, micro Raman spectroscopy and transmission electron microscopy for material parameters measurements. Accordingly, Raman to stress/strain relationships of the tested material for a specific crystal orientation is analysed theoretically. Finally, from the Raman map results, the residual stress distribution is evaluated.

Tsirka et al. (2018) have successfully tested the Raman strain sensing on advanced smart structural materials such as carbon nanotube coated carbon fibres. Chen et al. (2020) have utilized the Raman spectrometer for high temperature applications. The Raman spectrometer was able to measure the residual stresses on the tested composite at temperatures as high as 1400 ºC.

2.9 Magnetic method

Magnetic method is sub categorized as – Magnetic strain, Magnetic memory, Magnetic noise and Magnetomechnical acoustic emission methods.

Magnetic strain method: magnetic strain is an observation and evaluation of the variation in size of the magnetized ferromagnetic test specimen. The changes in the form of magnetic resistance is measured to evaluate the residual stresses in the tested ferromagnetic specimen. The method is found to be vulnerable due to its approach of using the boundary conditions for calculation, and have a tendency to show errors in the case of stress readings that are higher than a certain range. Therefore, currently this method is restricted to measurements of stresses of certain range and beyond that range is not recommended.

Magnetic memory method: magnetic memory is an after effect observed in the form of residual magnetization of tested specimen. This method is a non-destructive method based on the analysis of 'magnetic leakage fields' distribution on test specimen, and can be utilized to analyse the defects, stress concentration zones, structural in homogeneity etc. The memory method is popular for the detection of stress concentration, but its accuracy is affected due to several factors such as quality of magnetic signals and the working environment. Singh et al. (2018) have proposed a method by combining giant magneto-resistive sensor (GMR) with metal magnetic memory (MMM) technique for the mapping of deformation induced magnetic leakage fields in the tested carbon steel specimen. Validation of experimental results with the numerical finite element model results showed great agreement and the proposed method successfully detected the plastic deformation. The authors also highlighted the influence of shot peening on the occurrence of residual stress. Kunshan et al. (2018) have proposed a diagnosis approach to improve the magnetic memory technique's performance in detecting the defects in welded joints. The proposed method is based on evaluating the changes in the intensity of the magnetic memory and gradients, and can be utilized to differentiate the welding defects from stress concentration zones.

Magnetic noise method & Magnetomechancial acoustic emission method: magnetic noise also known as Barkhausen noise method (BN) is famous for surface residual stress measurements in ferromagnetic materials. Ferromagnetic materials consist of magnetic regions named domains, rotates during magnetization. The sensor senses the presence of residual stressby recognizing the changes in permeability caused by the stress. The observed BN signal is then compared with the signal from the stress free state in order to evaluate the residual stress. Magnetomechanical acoustic emission method is similar to magnetic noise method except for the type of signals collected for the measurement of residual stress. Acoustic emission sensors such as piezoelectric devices are used and the rest of the setup is identical to magnetic noise method. Major concern regarding these methods are the interpretation of signal and data collection systems used in the setup. Set up preparation, quality of the devices (ex: amplifier, oscilloscope), frequency settings are considered as the factors needing more attention and some of the best methods are well discussed by the researchers (Sanchez et al., 2017; Wang et al., 2018).

2.10 Nano indentation method

This is one of the newly invented method for residual stress measurement. There are two ways this method can be used for residual stress measurements. One is using the P-h curve of the nanoindentation by analysing the effect of residual stress on it with the help of loading and unloading curves. The other method is based on the concept of fracture mechanics, where the lengths of the cracks produced by the indentations on the stress regions are compared with that of the regular cracks on unstressed regions. Nanoindentation method is seen to have incomplete theory and there has been efforts by researchers to prove it wrong. There are several theoretical models available for evaluating the residual stresses – Suresh model, Lee model, Xu model, Swadener model and their applicability is well discussed by Wang et al. (2018). Mann et al. (2014) have investigated the residual stress on the peened surface of aluminium alloy 2024-T351 by combining the nanoindentation with numerical simulations using ABAQUS software. The experimental results showed the highest hardness near the peened surface and the maximum compressive residual stress at the sub-surface and closer to peened surface. The validation results showed the effectiveness of coupling the nanoindentation method with numerical simulation for the peened aluminium surfaces. Kim et al. (2018) have proposed a modified Barkovich indentor with height to base ratio of 2.6:1 for the evaluation of stress directionality. They tested it on various materials and obtained the conversion factor values from the slope in relation to stress and indentation load difference.

Table 2

Summary.

Methods		Highlights
Destructive	Hole drilling – strain gauge method	• Isotropic elastic materials • Relatively low cost instrument • Relatively low accuracy in the category (±50 MPa) • Data interpretation through strain gauges causes inaccuracies
	Hole drilling – ESPI method	• More precise than strain gauge method (±20 MPa)
	Ring core method	• More precise than Hole drilling methods (±10 MPa)
	Stripping method	• Hard film materials • Fully destructive • Non uniformity in material removal • Relatively low accuracy in the category (±50 MPa)
	Crack compliance method	• Materials with low stress amplitude. Not suitable for high stress measurements • Simple and economical • Not suitable for complex structures
	Contour method	• Precise than stripping and crack compliance methods (±20 MPa) • High variation in stress gradient • Proven to be good for welded parts
Non destructive	Diffraction (X-ray) method	• Isotropic elastic crystal materials • High accuracy (±20 MPa) • Minimal damage to materials • Expensive instrument
	Ultrasonic method	• Metals • High accuracy (±20 MPa) • Applicability on thicker and larger components • Flexible, safe and less expensive among the non-destructive methods
	Raman spectroscopy	• Capable of measuring non-uniform stresses • Highly vulnerable to factors - room temperature, focussing inaccuracies, data recording method etc.
	Magnetic	• Restricted to only ferromagnetic materials • Relatively low accuracy • Strain method: Restricted to stress measurement in a certain range and is not recommended beyond that range. • Noise & Magnetomechnical methods: Signal interpretation and data acquisition is an issue
	Nanoindentation	• Film materials • Incomplete theory

From the simulation study, the other tested indentors with different geometries were also able to predict the conversion factors. From their findings, the authors proposed this new method using a new shape of indentor without the contact area function. Martinez et al. (2019) have tested the nanoindentation method for residual stress investigation in the welded zone of micro alloyed steel, which was produced using Autogenous gas tungsten arc welding. Nanoindentation tests are performed on various locations of the welded zones, subzones of the heat-affected areas, and from their findings, they were able to identify the exact locations with tensile residual stresses and compressive residual stresses. They proposed a modification for indentation locations in order to calculate the actual contact area and determine the residual stresses.

3. Summary and Discussion

After years of research and development, a variety of testing methods have been developed and applied. Some of the advantages and disadvantages of these different methods are summarized and given in Table 2. From the summary of each of these methods, every method has its own limitations and the selection of appropriate method is completely reliant on the requirement of the user. For example, it is obvious that the destructive methods are not a popular choice in machining related researches due to the harm they cause on the microstructure of the test materials. By considering this criterion, non-contact type seems to be the solution for the researchers and industries in order to reduce the wastages. However, destructive methods such as hole drilling, ring core methods have the flexibility of onsite applications and require relatively low cost instruments compared to non-contact type (ex: XRD). In the review, the attempts made by the researchers in the recent years using combination of two or more methods to improve the detection accuracy is observed. There is significant progress in the area of accuracy improvement using the combination of two – three methods approach, and needs further developments to establish a single method that has the combination which is less-destructive, economical and highly accurate.

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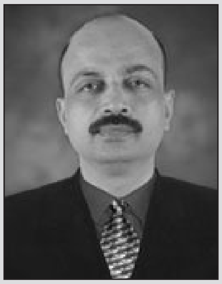

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