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Experimental Techniques to find Thermal Residual Stress in Composite Materials –A study of the Literature Review

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Abstract

If two dissimilar materials are joined at high temperature, a very high residual stresses developed near the interface of materials. The mismatch between the co-efficient of thermal expansion leads to stress concentrations at the interface. These Residual stresses were found to affect the composites matrix-dominated, mechanical and durability properties, as well as to inflict damage and dimensional instability. Over the last years several methods have been developed to measure the residual stresses. This paper aims to explain the different experimental methods to measure residual stresses and to provide overview of advancement in this area to help researchers to choose on their applications.7

Keywords: Residual Stresses, Neutron Diffraction, Contour Method.

Introduction

Metal matrix composites (MMC) have become increasingly attractive in recent years for their high strength and creep resistance properties [1-3]. MMC is a composite material which contains metal as the matrix compound. The matrix (e.g. aluminum) is usually a ductile material and has higher elasticity when compared to the reinforcement material which has also ductile material properties [4]. The reinforcement (e.g. Glass fiber) material has higher strength and toughness when compared to the matrix material. An MMC such as glass fiber and aluminum matrix composite higher mechanical properties than aluminum and lighter than steel. Thus, its usage in many engineering applications endures.

Since residual stresses are inherently present in virtually all composite materials and influence the properties of the composite structures significantly , it is of utmost importance that the thermal residual stresses are taken into account in both design and analytic modeling of composite structures[5,6] . Predictive models for thermal residual strains and stresses in composites require verification and validation with experimental results. Many experimental techniques for residual stress determination in polymer matrix composites have been developed in the past , mostly based on techniques that are frequently applied to metallic structures. A good summary of these methods was given in Ref. [7], where the experimental techniques were categorized in two classes: destructive techniques and non-destructive techniques.

The engineering properties of materials and structural components, notably fatigue life, distortion, dimensional stability, corrosion resistance, and brittle fracture can be considerably influenced by residual stresses [8].

Understanding the residual stresses

Residual (locked-in) stresses in a structural material or component are those stresses that exist in the object without (and usually prior to) the application of any service or other external loads. Residual stresses are the stresses which are remained within material or body because of the material processing or mismatch of co-efficient of thermal expansion(CTE). They can also be produced by service loading, leading to inhomogeneous plastic deformation in the part or specimen. Residual stresses can macro or micro stresses or both can be present at the same time.

Classification of residual stresses can be given as follows

Type I: Macro residual stress that develop in the body of a component on a scale larger than the grain size of the material;
Type II: Micro residual stresses that vary on the scale of an individual grain;

Type III: Micro residual stresses that exist within a grain, essentially as a result of the presence of dislocations and other crystalline defects

Reason for generation of residual stresses

Residual stresses are induced during processing of material involving material deformation, , machining or processing operations, heat treatment that transform the shape or change the properties of a material. Residual stresses generated between the matrix and the fibre during cooling from the processing temperature (more precisely, the stress-free temperature.

The effects of residual stress may be either beneficial or detrimental, depending upon the magnitude, sign, and distribution of the stress with respect to the load induced stresses. Very commonly, the residual stresses are detrimental, and there are many documented cases in which these stresses were the predominant factor contributing to fatigue and other structural failures when the service stresses were superimposed on the already present residual stresses. The particularly insidious aspect of residual stress is that its presence generally goes unrecognized until after malfunction or failure occurs.

Effects of thermal residual stresses

A tensile strain will be developed in the matrix material. Locally, the magnitude and even sign of this strain may vary due to variations in fibre volume fraction [9,10]. In composites the fibre matrix adhesion occurs due to the shrinkage of the matrix around the fibre and there by increasing the Van der Waals bonds between the fibre and the matrix [11]. The fibre–matrix interfacial bond strength is of influence on the magnitude of residual stresses.

Residual stresses induce the following effects
I) Fibre waviness
ii)Transverse cracking
iii)Delamination
iv)Warpage of laminates

Experimental techniques

In past several years many techniques have been developed to find the residual stresses. This paper explains the different techniques available for researchers on selecting their techniques. The techniques for find residual stresses may be classified as destructive or semi destructive or non-destructive techniques. These methods depends on the measurement of deformations caused by residual stresses upon removal of material from the specimen. Destructive and semi destructive principal includes Sectioning, contour, hole-drilling, ring-core and deep-hole. Non destructive methods include X-ray or neutron diffraction, ultrasonic methods and magnetic methods. These techniques usually measure some parameter that is related to the stress.

Destructive method

Destructive method that relies on the measurement of deformation due to the release of residual stress upon removal of material from the specimen. It has been used extensively to analyze residual stresses in structural carbon steel, aluminum and stainless steel sections[12,13]. Figure 1 shows different methods to find residual stresses

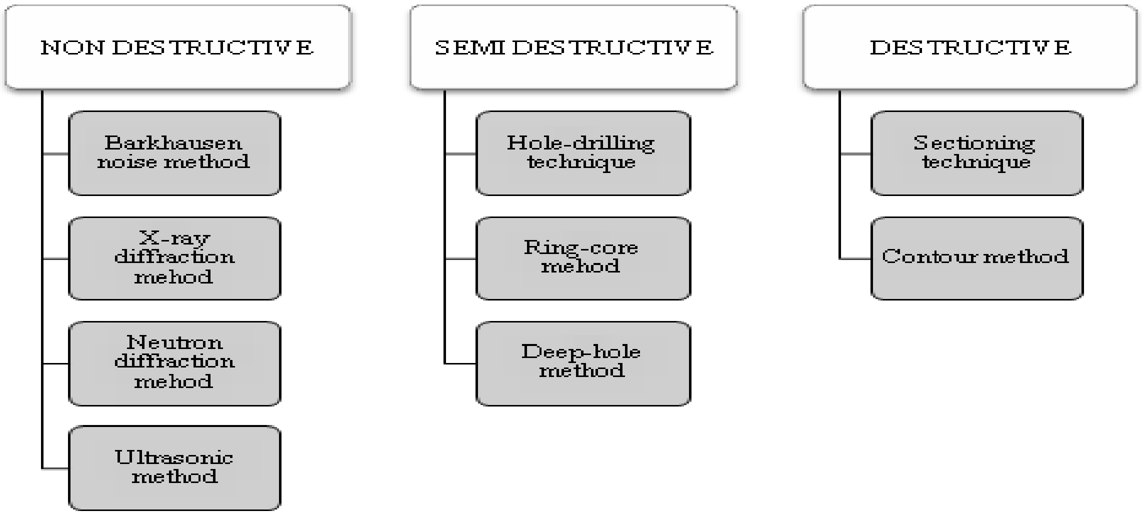

Figure 1: Residual stresses measuring techniques.

Sectioning

The "sectioning method", is based on the principle that internal stresses are relieved by cutting tlhe specimen into many strips of smaller cross section. The method is best applied to members when the longitudinal stresses alone are important. The sectioning method includes making a cut on an instrumented plate in order to release the residual stresses which are present on the cutting line.

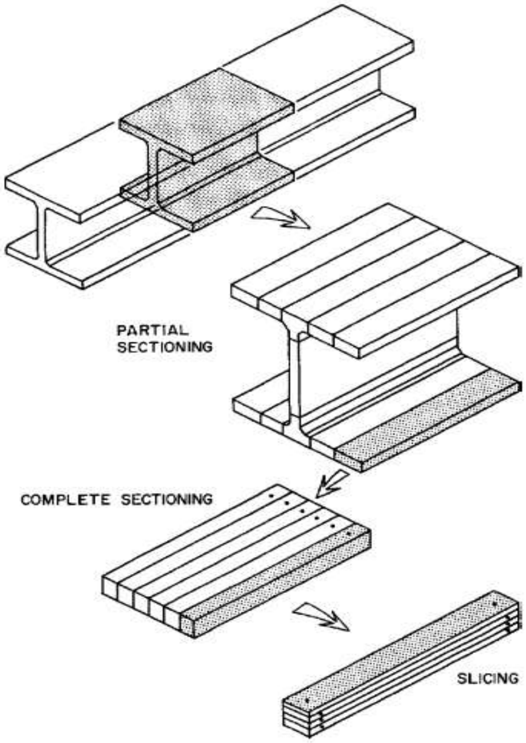

Fig 2: Sectioning method[14]

For this, the cutting process used should not introduce plasticity or heat, so that the original residual stress can be measured without the influence of plasticity effects on the cutting planes surface. Figure 2 shows an example of the sectioning method, where a sequence of cuts was made to evaluate the residual stresses in an I-beam section [14]

The strains released during the cutting process are generally measured using electrical or mechanical strain gauges.

Contouring Method

The contour method has been developed by M B Prime at Los Alamos National Laboratory [15]. It consists of the measurement and analysis of a cut-surface in the plane where residual stress is to be determined. The stress relief because of the cut creates a deformation field which can be measured and then used to infer the residual stresses that were present at the plane of interest before the cut was made.

The procedure is divided into four main phases which are described in this section

Cutting

The cut is done by wire electric discharge machining (wEDM), because according to Prime et al. [16] this process introduces less residual stresses which could influence the result, than other cutting methods. Wire electric discharge machining removes material by spark erosion. The surface of the cut has a very good finish, which simplifies the data treatment procedure needed to smooth the measurement data of the deformed surface

Cut-surface measurement

The surface of the wEDM cut has to be digitized in a way that permits the introduction of gathered data into a finite element model.[15] The measurement is done using a touch probe with an 1 mm diameter Renishaw ruby tip on a Brown & Sharp CMM, model Gamma, since it meets the precision requirements. Measurements were taken along the centerline.

Data preparation

In order to be able to apply the measured data to a finite element model, this data has to be prepared. The measured geometry has to be translated into nodes and elements which define the mesh used, and the noise must be filtered out of the deformation measurement. Most of the data preparation is done within the MATLAB programming environment.

Modeling

A linear elastic finite element model is chosen to serve as a calculation base for the expected residual stresses.

In the conventional contour method, the measured displacements are used to predict the original residual stress. In contrast, the principle of the multi-axial contour method is based on computing the eigenstrain from the measured displacement, and then the residual stresses are derived from the eigenstrain. The source of all residual stresses is incompatible strain in a body which is the so-called eigenstrain. Many researchers [17 – 19] have studied residual stresses in engineering components using eigenstrain.In other words, a change in the geometry of a body alters the residual stress distribution but not the eigenstrain

Other destructive methods

There are some other destructive methods available like excision, splitting, curvature, layer removal and slitting, are described as follows.

Excision

Excision is a simple quantitative method for measuring residual stresses. It entails attaching one or more strain gauges on the surface of the specimen, and then excising the fragment of material attached to the strain gauge(s). This process releases the residual stresses in the material, and leaves the material fragment stress-free. Excision is typically applied with thin plate specimens [20].

Layer Method

The layer removal method is a generalization of Stoney's Method. It involves observing the deformation caused by the removal of a sequence of layers of material. The method is suited to flat plate and cylindrical specimens where the residual stresses are known to vary with depth from the surface, but to be uniform parallel to the surface. Figure 3 illustrates examples of the layer removal method, (a) on a flat plate specimen, and (b) on a cylindrical specimen.

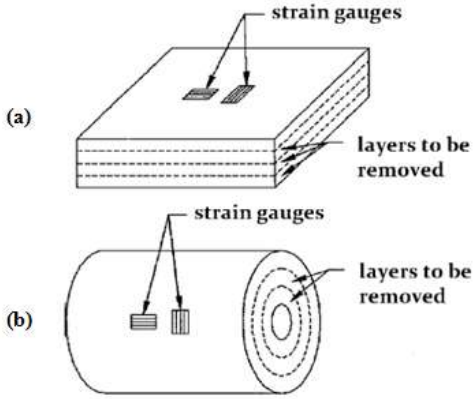

Figure. 3: Layer removal method, (a) flat plate, (b) cylinder [21].

The method involves measuring deformations on one surface, for example using strain gauges, as parallel layers of material are removed from the opposite surface.

Slitting method

The slitting method [22-24] is also very similar to the hole-drilling method, but using a long slit rather than a hole. Figure 4 illustrates the geometry. Strain gauges are attached either on the front or back surfaces, or both, and the relieved strains are measured as the slit is incrementally increased in depth. The slit can be introduced by a thin saw, milling cutter or wire EDM. Due to this, the residual stresses perpendicular to the cut can then be determined from the measured strains using finite element calculated calibration constants, in the same way as for hole-drilling calculations.

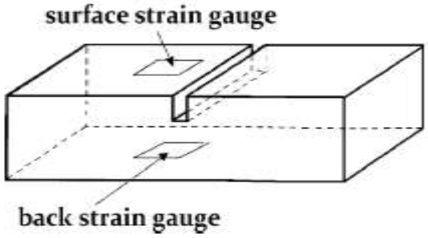

Figure 4: Slitting method [22].

Semi destructive Technique

Semi destructive method of measuring residual stresses are as follows: Hole-drilling, ring-core and deep-hole

Hole drilling

It is one of the most popularly used semi destructive methods of residual stress evaluation which can provide the measurement of residual stress distribution across the thickness in magnitude, direction and sense.

The principle involves introduction of a small hole (of about 1.8 mm diameter and up to about 2.0 mm deep) at the location where residual stresses are to be measured. Due to drilling of the hole the locked up residual stresses are relieved and the corresponding strains on the surface are measured using suitable strain gauges bonded around the hole on the surface [25]. From the strains measured around the hole, the residual stresses are calculated using appropriate calibration constants derived for the particular type of strain gauge rosette used as well as the most suitable analysis procedure for the type of stresses expected [26]

Non-Destructive methods

Non-destructive methods are based on measurements of electromagnetic, optical and other physical phenomena in the residual stress zone. The common methods among this category are as follows.

Magnetic Barkhausen noise(MBN) method

The magnetic Barkhausen noise (MBN) method is of particular advantageous because of its potential as a non-destructive industrial tool to measure surface residual stress (SRS) and other parameters. MBN technique is applicable to ferromagnetic materials. The materials are magnetized along the easy axes of the crystallographic magnetization direction. Domains are separated each other by domain walls also called Bloch walls. There are two types of Bloch walls in a ferromagnetic material. 180° Bloch walls have greater mobility than 90° walls so their contribution to MBN is bigger [27]. When all electrical pulses producedby all domain movements added together a noise like signal called as

Barkhausen Noise is generated [28]. Figure 5 schematically shows the design of a micromagnetic sensor.

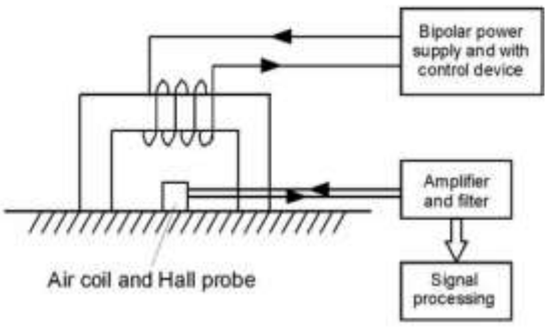

Figure. 5: Micromagnetic sensor setup [29].

A U-shaped yoke is excited by a coil connected to a bipolar power-supply unit. By the orientation of the poles, the direction of the resulting alternating magnetic field is defined and thus the corresponding stress component can be measured. The Barkhausen noise is detected by a small air coil whereas the tangential field strength is measured by a Hall probe. Both signals are amplified, filtered and evaluated in the micromagnetic testing system [29].

X-ray diffraction method

The X-ray method is a non-destructive technique for the measurement of residual stresses on the surface of materials. X-ray diffraction techniques exploit the fact that when a metal is under stress, applied or residual stress, the resulting elastic strains cause the atomic planes in the metallic crystal structure to change their spacings. X-ray diffraction can directly measure this inter-planar atomic spacing; from this quantity, the total stress on the metal can then be obtained[30,31].

X-ray diffraction residual stresses measurement is applicable to materials that are crystalline, relatively fine grained, and produce diffraction for any orientation of the sample surface. Sample may be metallic or ceramic, provided a diffraction peak of suitable intensity and free of interference from neighboring peaks can be produced in the high back-reflection region with the radiations available [32].

Neutron diffraction method

Neutron diffractions method is very similar to the X-ray method as it relies on elastic deformations within a polycrystalline material that cause changes in the spacing of the lattice planes from their stress-free condition. The application of neutron diffraction in solving engineering relevant problems has become widespread over the past two decades. The advantage of the neutron diffraction methods in comparison with the X-ray technique is its lager penetration depth. In fact the X-ray diffraction technique has limits in measuring residual stresses through the thickness of a structure. A neutron is able to penetrate a few centimeters into the inside of a material, thus it can be applied widely to evaluate an internal residual stress of materials. It enables the measurement of residual stresses at near-surface depths around 0.2 mm down to bulk measurement of up to 100mm in aluminum or 25 mm in steel [33].

Ultrasonic method

Ultrasonic method is called also refracted longitudinal (LCR) wave technique. Ultrasonic stress measurement techniques are based on the acoustic-elasticity effect, according to which the velocity of elastic wave propagation in solids is dependent on the mechanical stress [34,35]. Different configurations of ultrasonic equipment can be used for residual stresses measurements. Overall, waves are launched by a transmitting transducer, propagate through a region of the material, and are detected by a receiving transducer, as show in Figure 6 [36].

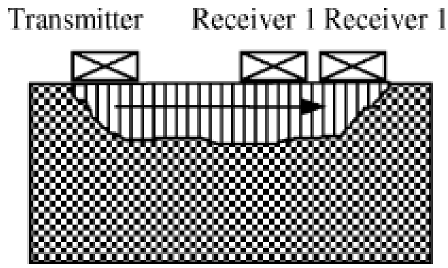

Figure. 6: Schematic view of ultrasonic measurement configuration: surface pitch-catch [36]

The technique in which the same transducer is used for excitation and receiving of ultrasonic waves is often called the pulse-echo method. This method is effective for the analysis of residual stresses in the interior of the material. In this case the trough-thickness average of the residual stresses is measured.

Conclusion

The destructive and semi destructive residual stresses measurement methods generally require much less specific calibrations because they measure fundamental quantities such as displacements or strains, thus giving them a wide range of application. The hole drilling method is a cheap, fast and popular semi destructive method. It could be applied to isotropic and machinable materials whose elastic parameters are known. The contour method promises to be a useful complement to existing methods, being the first destructive method to provide high-resolution maps of the stress normal to the cut surface.

The non-destructive residual stresses measurement methods have the advantage of specimen preservation from destruction, and they are particularly useful for measurement of valuable specimens. These methods commonly require detailed calibrations on representative specimen material to give required computational data. Polycrystalline and fine grained materials requires the diffraction method like X-ray and Neutron diffraction. The advantage of the neutron diffraction method in comparison with the X-ray technique is its lager penetration depth as x-ray method is limited for the measurement of residual stresses on the surface of materials. The magnetic Barkhausen noise (MBN) method is applicable to ferromagnetic materials.

The following remarks should be considered when choosing the residual stress measurement techniques.

1. Contour method is a destructive method has a high resolution and can be used to high range of materials and for large components.
2. Sectioning method is fast and can be used for a wide range of materials but it is a destructive method and has a limited strain resolution.
3. X-ray diffraction method can be used for ductile materials to obtain both macro and micro residual stresses, but it is a lab based Methods and can be used for small components.
4. Neutron diffraction has an optimal resolution but it needs an expensive and specialist Facilities.
5. Synchroton method is fast method for both macro and micro residual stresses, but it needs a very special equipments.

Finally, in the Table 1 are summarized the advantages and the disadvantages of each methods

Table 1: Comparison of the residual stresses measurement techniques.

Techniques	**Advantages**	**Disadvantages**
X-ray diffraction	Ductile Generally available Wide range of materials Hand-held systems Macro and Micro RS	Lab-based systems Small components Only basic measurements
Hole Drilling	Fast, Easy use Generally available Hand-held Wide range of materials	Interpretation of data Semi destructive Limited strain sensitivity and resolution
Neutron Diffraction	Macro and Micro RS Optimal penetration & resolution 3D maps	Only specialist facility Lab-based system
Barkhausen Noise	Very quick Wide sensitive to Microstructure effects especially in welds Hand-held	Only ferromagnetic materials Need to divide the microstructure signal from that due to stress
Ultrasonic	Generally available Very quick Low cost Hand-held	Limited resolution Bulk measurements over whole volume
Sectioning	Wide range of material Economy and speed Hand-held	Destructive Interpretation of data Limited strain resolution
Contour	High-resolution maps of the stress normal to the cut surface	Destructive Interpretation of data

	Hand-held Wide range of material Larger components	Impossible to make successive slices close together
Deep hole drilling	Deep interior stresses measurement Thick section components Wide range of material	Interpretation of data Semi destructive Limited strain sensitivity and resolution
Synchrotron	Improved penetration & resolution of X-rays Depth profiling Fast Macro and micro RS	Only specialist facility Lab-based systems

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