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Shape distortion in composites: sources, characterization, and remedies

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ABSTRACT

This paper reviews the shape distortions in a polymer composite, its sources, characterization techniques, and remedies. The shape distortion may include warpage, spring-in, or change in enclosed diameter for flat, angled, and circular parts. Residual stresses are considered to be the major source of shape distortion (dimensional instability) in laminated composites. These stresses are the result of the difference in thermal expansion behavior of the different plies or between matrix and reinforcement. Additionally, fiber buckling, transversal cracking, and delamination are also produced in the composite, affecting its mechanical properties like tensile, flexural, and compression. The produced residual stresses are determined through different techniques like layer removal of symmetrical laminates, first ply failure, and x-ray diffraction. The common remedies for shape distortion reported in the literature include nanoparticle addition and variable thickness at the base or flanges.

1. Introduction

Composite materials are described as combining two or more materials, the final product has superior properties as compared to the properties of individual constituent materials [1–7]. The composite based on different natures of the discontinuous phases is called a hybrid composite [8,9]. The matrix forms the continuous phase and the reinforcement forms the discontinuous phase. The role of reinforcement is to bear the load and the matrix ensures the structural integrity of the composite [10–12]. Polymer nanocomposites are being used since the 21st century. They are formed by incorporating organic or inorganic fillers of 1-100 Å and a polymer matrix as a continuous phase [13,14–19]. For the preparation of composites, the polymeric matrices including, thermoplastic polymers like polyolefins, polyesters, polyamides, etc., and thermosetting polymers like epoxy, vinyl ester, unsaturated polyester, etc. are used for research and different applications at the industrial level [20–24].

Residual stresses persist in the materials after the removal of external load. These residual stresses can cause permanent failure in the structure. These may be due to the temperature gradients, plastic deformations, and structural changes as a consequence of phase transformation. The residual stresses formation in composites can cause failures in the composites, particularly when the tensile stresses are greater than the tensile strength of the material. At this point, microcracking can occur, which exposes the fibers to microbial and chemical attacks. Shape distortion is referred to as "true distortion". It is described as the misrepresentation of the shape (length or width) of an object. This is due to the alignment of the beam/part. The primary source of shape distortion is the free expansion and contraction of the material [25–32].

2. Shape Distortion

2.1 *Warpage of Laminates*

Interlaminar residual stresses cause a variety of curved shapes called warpage in thin unsymmetrical laminates [29,33,34]. For the confirmation of residual stresses in uniform cross-ply laminates or to check the effect of changing processing conditions on residual stresses, curvature measurements are used [35]. By increasing the temperature, thermal residual stresses decreased which results in a decrease in warpage. Additionally, the occurrence of micro-cracking in laminates lowers the curvature in non-symmetrical laminates [36]. Tool-part interaction and unstable cooling can cause dimensional instability in composite structures or warpage [37]. This can be due to the non-uniform thermal residual stress. For the measurement of stress dispersion across the thickness of composite structures and plates upon variation in temperature on both sides of the product different models have been developed [38–40]. For thin products, tool-part interaction has a prominent effect on warpage. For the rubber press forming process, the uneven temperature diffusion in molds or press plates can cause warpage.

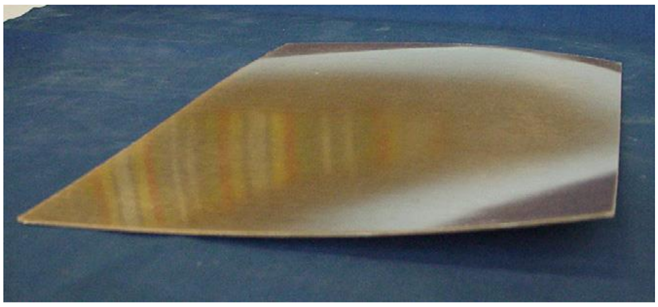

Fig. 1. Buckled glass fabric reinforced with polyetherimide laminate [41]

2.2 *Spring-in In Laminated Composites*

The in-plane contraction in almost all composites is very small than the out-of-plane contraction. That is the reason, the inner plies shrinkage is further controlled in the process of cooling. In the molding process, the sheet is immediately deformed as a result of an increase in the part residual stresses and after further cooling, the warpage is increased. A smaller enclosed angle will produce when a curve is formed in the sheet. The change in the internal angle is called the ‘‘spring-in effect’’.

Additionally, the interaction of tools part, thermal, and fiber volume gradients in the cooling process, ply stacking order, processing conditions, and uniformity of lay-up, also the environmental situations, like moisture can affect the spring-in of the laminates. Geometrical dimensions play an important role, like tool radius, enclosed angle, and part thickness.

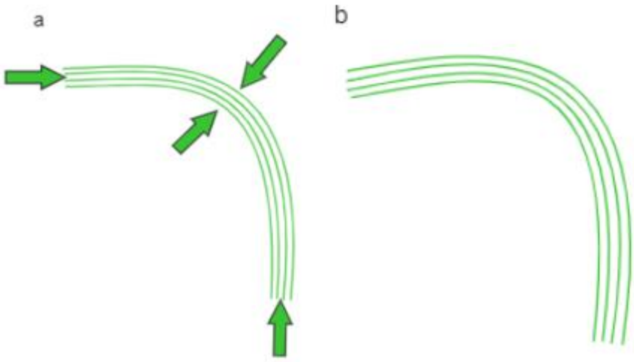

Fig. 2. Spring-forward schematic representation: (a) in-plane contraction before consolidation represented with the dotted arrows, and out of- plane contraction with the solid arrows, (b) cooling after consolidation.

Through-the-thickness residual stresses which developed as a consequence of the interaction of tools part or uneven cooling and interlaminar residual stresses with a non-uniform lay-up can begin the sides of the angled portion to deform and make another change in angle. Additionally, after thermoforming, it seems very difficult to achieve an even thickness distribution, which can produce more residual stresses. The spring-in reaction has inference for the double curvature and three-dimensional parts production. Different models were designed that project the ultimate distortion, spring-in angle, and warpage of a product, also the residual stress distribution. Models are complying with thermoelasticity, classical laminate theory (CLT), and viscoelastic behavior. The major aim for the forming of these models is to show the accurate design of the mold and to get the required dimensions of products for assembly. For different angular parts, the mold correction is between 1 and 2.5, but this also requires some adjustments when the lay-up, material system, and processing conditions are changed. This spring-in could be helpful for processing and mold designing because in molds with a 90° angle, the coupling pressure is very low in the side wall to confirm actual composite coupling. As a result of the spring-in effect, the angle in the female and male molds should be more than 90° during the designing of the mold, which applies maximum pressure to the walls of the mold for a good quality product.

3. Sources of Stresses for Shape Distortions

The residual stresses producing shape distortions in CFRP composite are due to different parameters. Researchers divide sources of stress which are involved in thermoset composites processing into extrinsic and intrinsic sources. Extrinsic sources are connected to process, which includes cure gradients and tool–part interaction, while intrinsic sources belong to part shape, lay-up, and material [25,42].

The sources of stress regarding processing parameters depend on the kinetics of the developed process, as well gradients in material morphology and thermal gradients. The environmental conditions are moisture absorption, temperature, and deformation of plastic during application. Fig. 3 shows a diagram that has ‘input’ variables on one side like material, geometry, and process, and the ‘output’ variables on the other side like residual stresses and shape distortions. These two types are similar to the intrinsic and extrinsic stress classes respectively.

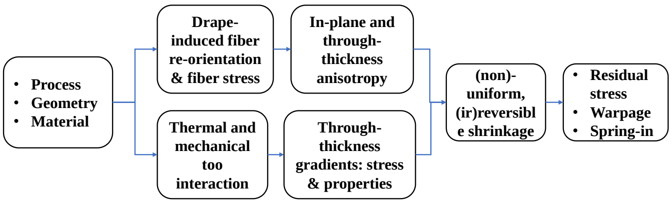

Fig. 3. The origin of warpage and residual stress in the processing of CFRP composite

The upper branch link to residual stresses produced due to the anisotropy and diversity of the composite material. The lower branch reports the stresses which appear from mechanical and thermal interaction with the tools throughout processing. Mechanical interaction means the produced stresses in a composite part formed by the mismatches in thermal expansion of tool and part material. Thermal effects produced more volume changes because of the shrinkage in polymer chains during the process of curing. This can produce major effects on the composite properties because atleast 7% volume change is observed in epoxy resin. Stresses can increases due to the difference in strains produced in tooling and part of the manufactured product in the curing process. The tools made up of steel or aluminum have higher expansion coefficients as compared to composites parts which results to stretch the parts upon heating. This can be due to the minor shear stresses in the tool which produce tension in the parts. Locking is another mechanism in tool part interaction in which the part geometry forces it to move with the expansion in tool. Filament wound tube is the best example induced tensile stresses are due to the manderal expansion [43].

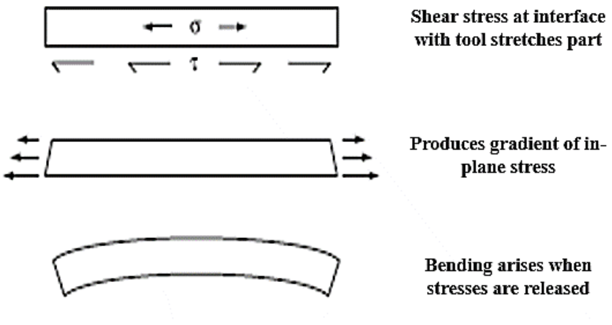

Fig. 4. Distortion at tool interface due to shear interaction

3.1 *Effects of Shape Distortion at the Fiber–Matrix Interface*

The fiber–matrix interface in thermoset composites is developed by using chemical bonds, while for thermoplastic composites this adhesion of fiber–matrix is because of the matrix shrinkage across the fiber which increases the Van der Waals forces between the matrix and fiber. On the other hand, the residual stresses affect the shear properties of the fiber–matrix effectively. Due to the increase in the radial residual stresses, the interfacial bonding of fiber–matrix becomes stronger due to the mechanical locking effects.

These produced residual stresses are due to the trans crystalline layers’ contribution. The strain-induced crystallization was produced in carbon fiber reinforced polyetheretherketone (PEEK) composites due to the thermal shrinkage mismatch behavior in the fiber and matrix. This behavior explains that, on the fiber surface, the polymer chains' strong anchorage presence is because of the strong chemical bonding, and thermal residual stresses produce orientation of chains in the polymer bulk which produces bulk nucleation for fast crystallization.

The reinforcing fibers have very good strength and residual stresses will not produce any important change in properties. But sometimes, fibers bear a compressive thermal residual strain in fiber direction from a certain load which was beyond the limit of the design of the fiber. That fiber crack was due to residual stresses.

3.2 *Effects of Residual Stress on Composite Structures*

In this section, we will discuss the residual stress effect on composite structures. In composite structures, due to machining of the manufactured composite structures, like cutting, drilling, etc., warping occur, due to the residual stress relaxation. Also, it was explained that in thicker composite parts, the residual stresses can affect the flexural stiffness, and structure buckling loads. In composite parts, residual stresses commonly produce dimensional instability in curved and angled parts. During cooling the composite structure shape changes due to the shrinkage behavior of the composites which originates due to the variation in thermal expansion behavior of the matrix and fibers.

4 Defects Induced By Residual Stresses

4.1 Fiber Waviness

The fibers bear axial loads like thermal residual stresses, while composite products were processed but the matrix is not able to provide any kind of transverse fiber support. Due to this reason, the shape of the fibers will change and waviness will produce [35]. We can say that the major effect of the residual stresses is fiber waviness [41]. On the other hand, high-temperature gradients around the laminate thickness also cause fiber waviness. A micrograph of the produced fiber waviness in composite laminates shown in Fig. 5 [33,44,45].

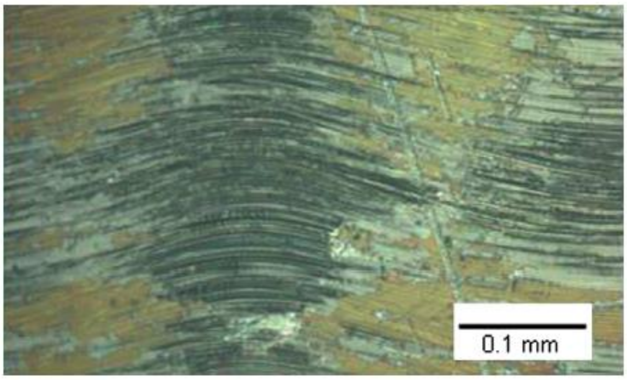

Fig. 5. Micrograph showing fiber waviness in a composite laminate [41]

4.2 Transverse Cracking

Thermal residual stresses can cause transverse cracking (microcracking) in composite laminates. Cracks will start when the thermal residual stresses in the matrix become more than the fiber matrix strength or resins yield strength which causes fiber matric debonding. When the interface bond is weak in the fiber matrix these microcracks will produce along with the interface. But if the interface is strong, these micro-cracks will propagate into the matrix [46–48]. In transparent composites, these microcracks may be visible or they might be too small and provide cracks initiation sites and thus reduce the service life of the composite. These produced failures are transverse ply cracking, delamination in adjacent ply and off-axis ply [48,49], and finally cracking of the laminate as shown in Fig. 6 [50,51]. These microcracks are prominent during cycling (fatigue) loading [52–54]

Some of the transverse cracking stages are identified as:

1. Matrix cracking/Fibre–matrix debonding.
2. Propagation of cracks in matrix /fiber–matrix debonding to form cracks.
3. Microcracks proceed in transverse ply cracks.
4. Delamination and failure of the laminate occur due to transverse ply cracks.

These cracks produce throughout the service life of composites. The following environmental factors like hygrothermal treatment [47, [55–58], aging [59,60], thermal cycling [61–65], UV radiation, and hygrothermal cycling increase the density of crack formation in thermoplastic composites. Additionally, residual stresses also cause sensitivity to solvents which leads to stress crack formation in nano thermoplastic composites [66–68].

Different reviews presented the effect of microcracks formation in thermoplastic composites [53,69]. Researchers have developed different analytical models from which microcracks formation due to external loading and due to thermal residual stresses can be projected [70–75].

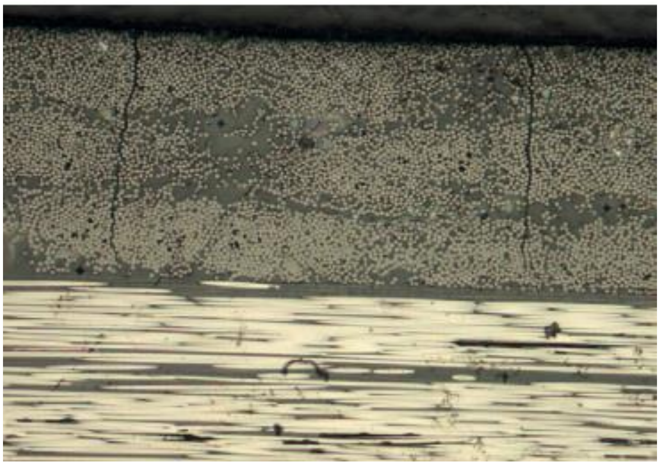

Fig. 6. Transverse cracks produced in 0°/90°/0° surface plies of carbon fiber [41]

4.3 Delamination

4.3.1 Delamination growth behavior

The delamination behavior observed in the fatigue testing of the nanocomposites or nanofibers shows that the specimens behave differently from that of virgin specimens. After the growth of delamination to some millimeters, a transition is observed in delamination propagation in Central Cut-Ply (CCP). At the start, the delamination propagates slowly after that the growth rate increases to that of new specimens. The demage surface shows that the crossings in the two nearest interlaminar become smaller upon the growth of delamination. Resultantly, both crossings meet at some point of delamination development after that the growth of delamination occurs by epoxy/glass fiber debonding. This delamination behavior is observed in interleaved samples of nanofiber [43,76].

4.3.2 *Effect of load intensity on delamination growth behavior*

At a small load level, the transition in delamination growth of interleaved nanofiber samples is present predominantly. But the delamination growth is constant at higher load levels. This mechanism is present at higher load levels on the failed sample's fracture surfaces. Small load level, the driving force is high for the interlaminar crossings suppression which leads to epoxy/fiber interfacial failure after several millimeters. In addition, at smaller strain rates the plasticity increases in the epoxy matrix [58] which leads to the driving force for interlaminar crossings suppression at smaller loads. The plasticity increases the matrix toughness [77].

5. Effects of Residual Stress on the Laminates Properties

The highest allowable external stress decreases if the residual stress and external load stresses are equal in sign [78]. The residual stress distribution affects the fatigue behavior, fracture toughness, and impact [66,79,80].

5.1 *Tensile*

Thermal residual stresses keep the matrix in a tension state at (0°) parallel to the fibers. While in transverse (90°) or radial direction the matrix and fiber experience the same state of stress either compressive or tensile respectively in the direction of 0° [52,81–83]. The tensile failure strain is increased in the fiber direction due to the fibers' compressive residual stresses [84].

When UD composites were fixed in tension parallel to the fiber direction, a prominent change in fiber strain was seen compared with bare fibers loaded in the air which was credited to the residual stress field [48,85, 86]. The residual stresses vary on different cooling rates that affect the tensile behavior of cross-ply PEEK, and IM6 carbon fiber composites [87]. The reaction of thermal residual stress was very small on the tensile reaction of thick-section hybrid carbon fiber and glass-reinforced PPS composites [84]. These stresses increase the ultimate tensile strength when studied with classical laminate theory (CLT). For unidirectional (UD), quasi-isotropic (QI) lay-up, and cross-ply this increase is very small. On composite moduli, the residual stresses have no effect.

5.2 *Flexural*

In a UD PP laminate reinforced with glass fiber, residual stresses lie between 45% and 37 % of the 90° 26 MPa flexural strength. The crystallinity level becomes decreases at high cooling rates but residual stresses increase. A competing effect is present in the viscoelastic relaxation of crystallization shrinkage and an amorphous portion of the matrix. The higher cooling rates affect the increases or decreases in residual stresses, which depend on the matrix crystallization kinetics [35].

5.3 *Compression and Shear*

The compressive properties of the polymer composite laminates decrease when the fibers experience compressive residual stresses [35]. Residual stresses always affect the transverse compressive loading [88]. Residual stresses formed fiber waviness which significantly disturbs the compressive properties [33]. Failure strain becomes decreases in compression tests and materials having different compressive and tensile elastic moduli. [84]. There is no published work that describes the relationship between residual stresses and shear properties.

5.4 *Creep and Fatigue*

In thermoplastic composites, the delamination shows the residual stresses from a major decrease in the specimen’s fatigue delamination strain [89]. The thermal residual stresses affect the composite laminates, and automatically matrix viscoelasticity exhibit relaxation and creep. At room temperature, the creep behavior was more prominent in rapidly-cooled samples in cross-ply IM6 carbon fiber PEEK laminates. On the other hand, the 90° direction-loaded unidirectional laminates have no difference in their creep behavior which shows that the variation in creep behavior cannot be individually involved in crystallinity level differences. In contrast, higher creep damage was found during transverse cracking and creep loading, because of the thermal residual stresses [30,59].

5.5 *Matrix-Dominated Properties*

Because of the shrinkage in matrix and fiber the matrix will experience thermal residual tensile strain. Due to the variation in fiber volume fractions the sign and magnitude of this strain may change. The magnitude of these strains can be predicted by using micromechanical models. It is difficult to present the residual stress effect on different matrix properties. But it’s easy to present the residual stresses effect on dominated properties of composites matrix, like temperature resistance and moisture absorption because the residual stresses significantly affect these properties. Tensile and share loadings decrease the glass transition temperature while compressive loads rise the Tg. The onset of the Tg is very important because it shows the high limit of processing temperature for different composites in numerous constructional areas. A group of researchers, present a low value of Tg carbon fiber reinforced polyetherimide

(PEI) composites as related to virgin PEI by using differential scanning calorimetry (DSC), due to the carbon fibers and the residual stresses. They also observed a decrease in Tg of 30°C in an quasi-isotropic 8-ply laminate, while a 6°C depression for a cross-ply 3-ply laminate was observed, that is due to the 42 MPa residual stress state. This 6°C Tg difference was constant for different heating rates. The residual stresses will be low upon increased temperature due to the difference in observed temperature, and expansion of the matrix . Different thermoplastic composites show linear behavior between residual stresses and temperature. Different effects take place: (a) matrix swelling changes the stress state; (b) plasticization of the resin because of moisture which lowers the glass transition temperature (c) fiber–matrix interphase, and (d) internal stresses affect, with the increase in the moisture uptake the residual stresses also increases. In pure polymers under tensile loads, the moisture uptake rate is accelerated. Due to the time-dependent viscoelastic behavior of the polymer matrix, the thermal residual stresses also show time-dependent behavior, while the matrix exhibit stress or strain relaxation behavior over the period. Polymers show increased values of the strain of the polymer matrix when placed in a fixed load. Increased residual stresses show a very higher relaxation rate. Different environmental conditions, e.g. moisture and temperature, affect this relaxation behavior. Experimental studies show that residual stresses in composites present through processing might reduce during storage in ambient hygrothermal parameters (50% relative humidity and 23°C).

Despite the effect of the thermal stress relaxation, one more time-dependent parameter that disturbs the matrix-dominated properties of composite: is the matrix aging effect. When a semi-crystalline polymer is cooled at lower Tg, a glassy solid is achieved having polymeric chains in a thermodynamic non-equilibrium state, and the material shifts to thermodynamic equilibrium then physical aging will occur. This property is called the changes in the enthalpy, entropy, and free volume of the polymer. Processing and temperature history has a strong impact on the physical aging rate, i.e. with an increase in temperatures (less then glass transition temperature), the physical aging rate is high and, during anealing, the effects of aging are more prominent. The composite matrix age shows in two manners: that is the effect of physical aging and relaxation of the polymer matrix prestressed state in a composite. The environment also takes part in the matrix aging phenomena. Isothermal or hygrothermal aging (holding relative humidity and a certain temperature for some time) interacts with residual stresses. In an oxygen environment, polymer matrix oxidation can convert the matrix into brittle, which results in decreasing the properties of composite like initiation of damage. Isothermal aging increases the Tg or stress-free temperature, while inert environments affect the composite properties to a minor extent.

6. Residual Stress Determination Through Destructive Testing

The destructive testing include curvature methods for Layer removal, first-ply failure, and stress-relaxation-based procedures.

6.1 Layer Removal of Symmetrical Laminates

The unsymmetrical laminates are obtained by the removal of layers from a laminate. [90]. The outer layer of the laminates was removed through milling (abrasion) [91–94]. The disadvantage of this technique is that it is not material friendly because during abrasion heat generation and microcracking initiation start which releases internal stresses during the investigation. In addition, the abrading technique also eliminates further property and structural evaluations. The damages produced by the abrasion technique were removed by using another method called the Rayleigh-Ritz method. This method excluded the measurement of released strains for residual stress calculations [95,96]. The process of simulated laminate (PSL technique) was introduced to prevent composites from damaging. In this technique, multiple composite prepreg plies were used which are separated by release plies e.g. polyimide foils [92]. These form a constitutive laminate (CL), which is separated after processing and then analyzed.

6.2 First, Ply Failure

The residual tensile stresses were created in the transverse 90° plies by the thermal contraction in symmetrical laminates. The laminate tensile strength $\sigma^t_{0/90}$, in which t superscript is for transverse direction, is calculated to be less than for transverse tensile strengths of unidirectional laminates $\sigma^t_{0/0}$. The tensile strength is measured by acoustic emission; thus this is called first ply failure. The variation in the values gives an approximate value for the interlaminar residual stresses σ_R [94][97]: $\sigma_R = \sigma^t_{0/0} - \sigma^t_{0/90}$.

6.3 Techniques Based on Stress-Relaxation

These are based on destructive techniques. In a destructive process, internal stresses are released by removing material. This produces distortions in the sample, which are then observed and compared to the deformations state prior to removal [98] [99]. The free surface generation in the composite relaxes the residual stresses which help to measure the originally present residual stresses in the laminate. These techniques are used for the determination of global residual stress distribution and lamination stresses. Different techniques like grooving and layer removal of laminates are used for the measurement of residual stress by relaxation. These methods are used for metals, continuous fiber-reinforced polymers, concrete, and unfilled polymers [99]–[103]. This method provides high accuracy[104]–[107].

6.4 X-Ray Diffraction (Non-Destructive Technique)

X-ray diffraction is a non-destructive technique for the determination of surface stresses. It can be combined with the layer removal technique for the generation of a stress profile, then this method becomes destructive.

XRD is based on the deformations in a polycrystalline material to determine the internal stresses in a sample. The deformations create changes in the spacing of the lattice planes from a stress-free value to a new value that is equal to the magnitude of the applied stress. In this technique X-rays of very high energy are penetrated on the surface of the specimen, and some portion of the X-rays are diffracted from the crystal planes following Bragg's law. The peak location helps to determine the stress in the component. Parallel-beam method and two-exposure method can also be used for the measurement of stresses in a material [108–112].

6.5 Other Stress Relaxation-Based Techniques

Blind-hole drilling technique is also used for the determination of residual stress based on stress relaxation. It can be used for all types of materials using the ASTM E837 testing standard [113].

In this method, a strain gauge rosette is placed on the sample and a small hole is drilled in the center of the rosette. Due to the removal of material stresses are released which changes the hole geometry and dimensions. The strain changes are measured and processed [98,114]. This method is also used with a combination of speckle interferometry [115–118], Moire´s interferometry, and holographic interferometry [119–122].

7. Factors Affecting Shape Distortion

7.1 Nanoparticles

Due to the shape distortions, manufacturing composite structures is very difficult and this causes an enhancement in costs. That is the reason, the understanding of thermal expansion and/or contraction is important to characterize the behavior (before and after production) and final utilization of composite materials. The researchers have paid attention to the study of the thermal expansion coefficients (CTE) of unidirectional composites, fiber orientation effect on CTE, out-of-plane thermal coefficients, and their numerical calculations. The epoxy composite filled with silica powder is used extensively for semiconductor device packaging. The silica fillers incorporation helps to lower the thermal expansion coefficient.

The incorporation of silica nanoparticles in composites reduces the thermal expansion coefficient (CTE). 6% addition of silica particles decreases the CTE to about 21% as shown in Fig. 7. This is due to the strong interaction between resin and filler [93–95]. The addition of silica particles increases the modulus and tensile strength of the resin [96]. The fillers have high strength than the resin so by increasing the concentration of particles modulus is also increased. The thermal stability of polymer matric is increased by the incorporation of alumina nanoparticles. The alumina nanoparticles act as insulators and mass transport barriers to volatile products forms as a result of decomposition. The thermal stability of the composites with nanoparticles is high than the pure acrylonitrile butadiene styrene (ABS) [97]. This is due to the increased interaction between alumina particles and the ABS chain, also with the increase in alumina particle loading levels, the thermal stability increased.

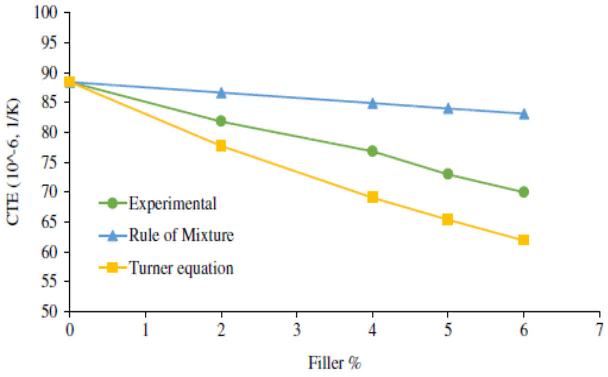

Fig. 7. Thermal expansion coefficients of silica nanoparticle-based resin [123]

The viscoelastic properties of pure ABS and ABS with alumina nanoparticles show that the storage modulus of the composites decreased with the incorporation of nanoparticles as compared to pure ABS. This is due to the addition of alumina particles which reduces the material stiffness during stiffness on ABS composites. Alumina nanoparticles increases the tensile strength at about 1–3 vol % and at 5% nanoparticle content the strength gradually decreased. This is due to the poor dispersion of alumina particles at 5% loading and the formation of agglomerate. These agglomerates debond from the ABS resin and the debonded alumina nanoparticles did not bear the external load and the tensile strength slowly decreased. By increasing the content of alumina particles the modulus is increased as compared to pure ABS. But the elongation at break value decreases upon the addition of nanoparticles.

7.2 Variable Thickness

Distortion angles; spring-in angle θ_β observed at the base and θ_{bw} spring-in angle measured at the flange tip counting the reaction of base spring-in and warpage is shown in Fig. 8 for the samples with 4, 8, and 12 plies, respectively. Four layered composites are considered to be thin (about 2.0 mm) which shows significant warpage according to CLT. But when the thickness of the composites increases it shows a reduction in the warpage as compared to base distortion because the middle layers balance the top and bottom gradient difference. So increased thickness shows a reduction in warpage.

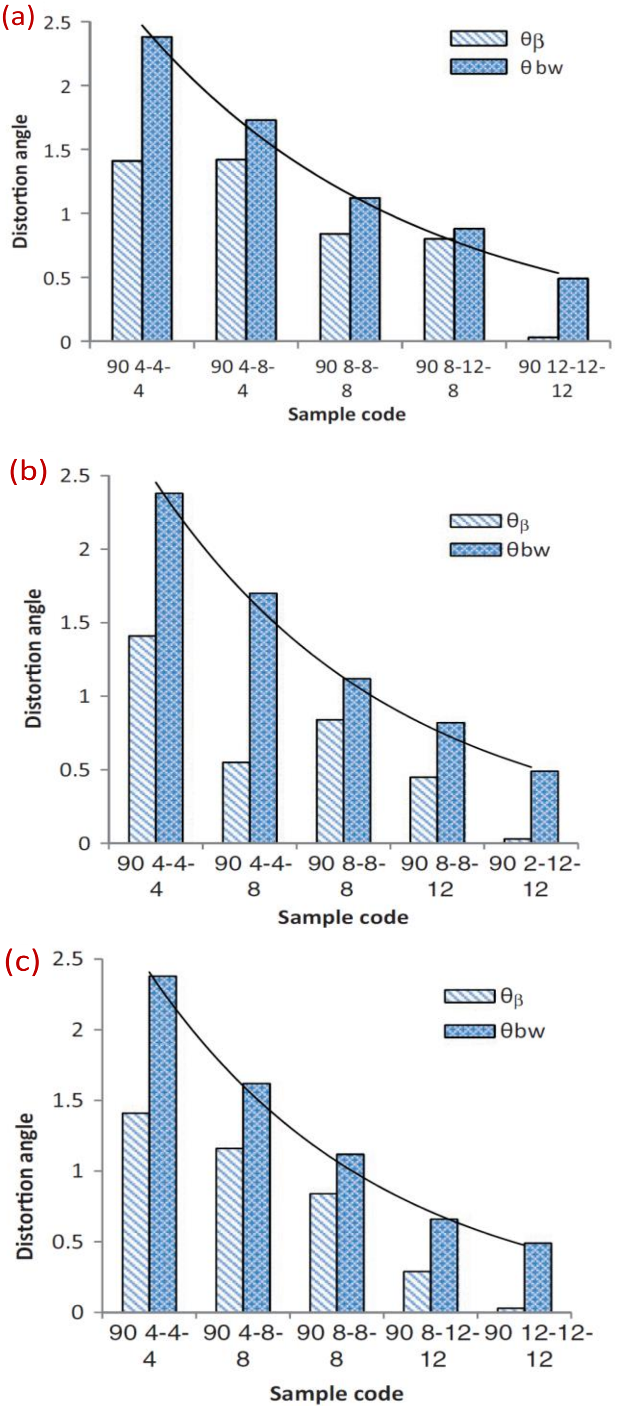

Fig. 8. (a) Thickness effect, (b) Flange thickness effect, (c) Corner thickness effect [124]

7.2.1 Flange Thickness Variation

By increasing the thickness at flange parts distortions becomes reduced as seen in Fig. 8(a). Uniform thickness parts have 1-3% less distortion than the flange part with increased thickness. Distortion can be reduced by reducing the warpage. Flange parts with increased thickness have 220-250% less warpage than the controlled samples. For both the controlled samples and increased thickness flange parts the base spring is the same, but there is a reduction in the value of θbw up to 27% and 37% in four and eight layers' flange parts.

7.2.2 Base Thickness Variation

At the base and controlled samples, increased thickness deformation behavior is shown in Fig. 8(b). Varying thickness parts show 1-3% less deformation than the average of extreme parts invariable thickness. With thickness variation from four to eight layers, there is a reduction in deformation from 40% to 37%. At base, thickness variation is more effective as compared to variation in flange thickness. Corner spring-in is lower in thicker corner parts because folding or corner play an important role in spring-in.

7.2.3 Varying Thickness at Flanges and Base Combined

There is a reduction in distortion up to (3-8%) by increasing flange and base thickness than the average distortion in upper and lower extreme parts with uniform thickness. These thickness variations are not hindering the reaction of each other and play their part individually in reducing the distortions, as shown in Fig. 8(c) contributing to significant reduction in deformation [124].

8. Conclusion

Different results of the thermal residual stresses in nanocomposites are discussed in this review article. In addition, different mechanisms like thermal or mechanical loading, residual stresses, and environmental changes all are involved to alter the material properties. The residual stress effects on shape distortion will be prominent only in the service life of composites due to the environmental effects and viscoelastic behavior interaction, including aging. The change in mechanical and physical properties of the matrix results in damage to the product, like toughness and glass transition temperature respectively. This is due to the debonding of the fiber-matrix interface. The thermal residual stresses significantly decreased the mechanical properties of composites. The most common defects formed by thermal residual stresses are warpage, transverse cracking, and fiber waviness.

9. Declarations

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Competing Interests

The authors have no financial or non-financial interests to reveal.

Author Contributions

The draft of this manuscript was written by Iqra Abdul Rashid and Khubab Shaker, and reviewed by Yasir Nawab. All authors read and confirm the final manuscript.

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