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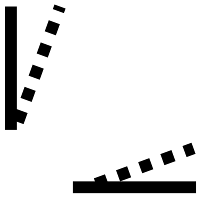
A276

Effect of shape in a RSDM system

Systems knowledge article



Document Type	Article
Document Identifier	276
Themes	• Residual stress and dimensional control management
Relevant Classes	• Shape
Tags	• Shape • Process-induced deformation • Integrated product development • Shape parameters

Introduction[edit | edit source]

The shape of a composite part can influence its residual stresses on a component scale (See Residual stress and dimensional control management (RSDM) for different scales of residual stresses and mechanisms). In other words, the shape of a part can influence its shape change during processing. The general geometry of the part (for example: L-shape or C-shape), curvature, use/presence of core, and part size are some of the major influencers.

Scope[edit | edit source]

This article discusses the impact of part shape on the residual stress and deformation of composite parts. The interaction between part shape and material properties such as cure shrinkage and thermal expansion/contraction leading to residual stress build up and deformation are discussed.

Significance[edit | edit source]

Deformations intrinsically associated with the shape, layup and size of a part should be considered during the design stage. For example, the angle change of an L-shaped bracket. If not controlled, the stresses and dimensional changes can cause matrix failure and increase manufacturing time and cost significantly. Since polymer composites shrink during cure and some are being cured at elevated temperature, residual stresses are impossible to eliminate completely. Thus, it is important to understand the potential deformation associated with the nominal designed shape.

Prerequisites[edit | edit source]

Recommended documents to review before, or in parallel with this document:

- General material properties
- Polymer properties
- Reinforcement properties
- Composite properties
- Heat transfer
- Thermal management
- System interactions
- Material (system class)
- Residual stress and dimensional control management

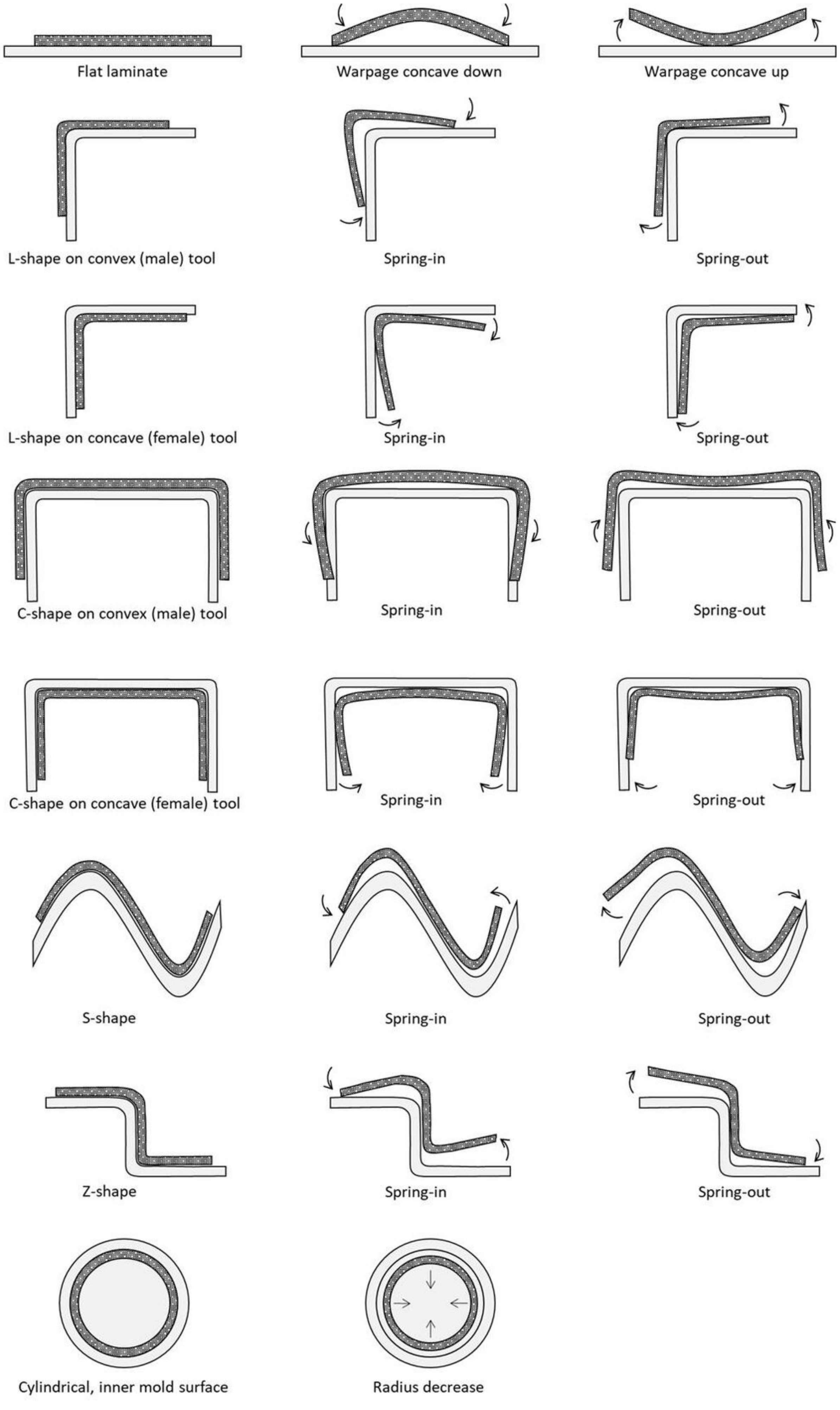
Analysis[edit | edit source]

The shape of a part implies the following parameters:

- General geometry: flat, L-shape, C/U-shape, S-shape, Z-shape, cylindrical or a combination of the geometries
- Corner radius
- Layup: fiber orientation and laminate thickness
- The use of core
- Part size: length and width

Effect of general geometry on RSDM[edit | edit source]

Given the general geometry, a number of possible deformation outcomes are shown in the table below. The deformation behavior in each case is driven by multiple factors including: tool-part interaction, layup, material anisotropy and environmental conditions such as physical aging or moisture absorption.



Flat laminate
Warpage concave down
Warpage concave up
L-shape on convex (male) tool
Spring-in
Spring-out
L-shape on concave (female) tool
Spring-in
Spring-out
C-shape on convex (male) tool
Spring-in
Spring-out
C-shape on concave (female) tool
Spring-in
Spring-out
S-shape
Spring-in
Spring-out
Z-shape
Spring-in
Spring-out
Cylindrical, inner mold surface
Radius decrease

Warpage for flat plates/sheets and large parts with very mild curvature (such as a wing skin) are mainly driven by tool-part interaction and layup. Tool-part interaction is discussed in more detail in Effect of tooling in a RSDM system and layup is discussed in Effect of layup on RSDM section below. Commonly, warpage can be observed as the part deforms to become either concave or convex with respect to the tool it was made on.

Spring-in can occur in any corner section of a part or curved areas. L-shape, C-shape, S-shape or Z-shape are prone to this type of deformation. Material anisotropy is the main driver for spring-in; it refers to the mismatch of through-thickness and in-plane cure shrinkage strain and thermal contraction strain. (See more details on material anisotropy on Residual stress and dimensional control management (RSDM)). As the composite part is being cured and subsequently cooled down from the processing temperature, the through-thickness strain is higher than the in-plane strain because fiber is not oriented in the through-thickness direction and the resin matrix will contract due to cure shrinkage and CTE. This strain mismatch causes the radius of curved areas to decrease. Another factor is that laminates at male corners can thin out due to pressure intensification. Whereas if bridging happens at females corners, there can be a lack of pressure which lead to increased thickness. This kind of deformation is commonly observed as the angle deviates from the tool after the part is made.

C/U-shapes and convex (male) portion of some S-shapes are prone to geometrical locking where the part is forced to expand/contract with the tool[1][2]. This can causing additional stresses to build up in the web and eventually more deformation. It was shown that with materials, tooling and equipment and all other processing conditions being the same, C-shapes have higher deformation than L-shapes by roughly 30% [3][4]. When the C/U-shape is locked to the tool, spring-in makes the two flanges clamp onto the tool, potentially making de-moulding difficult.

Effect of corner radius on RSDM[edit | edit source]

Studies in literature disagree on the effect of corner radius on spring-in of L-shapes. Throughout history, and with various material systems, many researchers have experimentally proven that corner radius has very little to no effect on spring-in [5][6][7][8][9][10][11]. However, the counterargument that corner radius could impact spring-in is equally strong and corroborated with experimental data. For example, Rennick and Radford isolated the thermo-elastic response from the non-thermal-elastic response as they heated up the cured L-shape specimens to curing temperature. They discovered as the specimen shape changed with increasing corner radius, the non-thermo-elastic contribution decreased. Whereas the thermo-elastic response was independent of the corner radius [12][13]. However, Radford stated that the phenomenon could be related to local corner thinning which was less severe for larger radii or other unknown corner radius related mechanisms. Jain et al. found that spring-in was independent of corner radius when radius-to-thickness ratios were greater than 1 [14]. Kappel et al. developed the largest physical dataset of AS4/8552 L-shapes with more than 200 specimens [10]. They discovered that unidirectional and bi-axial layup L-shapes have increasing spring-in with increasing corner radius, whereas this same trend did not exist in quasi-isotropic and cross-ply specimens. Last but not the least, Roozbehjavan et al.'s simulation results showed that spring-in increases with corner radius for [0/45/90/-45]4 L-shapes [4].

This disagreement within the literature could potentially be due to the narrow bandwidth of processing conditions and geometries such as corner radius, flange length and laminate thickness considered in the individual studies. A recent meta-analysis pooled experimental data of three representative materials systems: HEXCEL AS4/8552, TORAY T800/3900-2 (and its variants) and CYCOM IM7/5320-1 in literature. The study showed no dependence of spring-in angle on the corner radius [15].

Effect of layup and laminate thickness on RSDM[edit | edit source]

Thickness and layup are two of the most thoroughly studied processing parameters that can significantly affect residual stress and part deformation. Composite materials are intrinsically anisotropic, meaning the residual stresses and deformation are different in different ply directions. For example, a unidirectional ply will expand very little in the 0° direction due to its low A272, while it will expand more in the 90° direction because it is dominated by the expansion of the matrix. Similar residual stresses occur at all ply interfaces with different orientations. If the laminate is not balanced and symmetric, warpage will certainly occur. A balanced laminate has the same number of plies in the -θ as in the +θ direction, while a symmetric laminate forms a mirror image on both sides of the middle of the laminate. An example of a balanced and symmetric laminate is [0/45/-45/90/90/-45/45/0], which can also be written as [0/45/-45/90]s. Note that in reality, very slight deviation of the ply orientations (1°-2°) can cause the layup to be un-balanced and produce warpage in thin laminates. These deviation are un-avoidable in hand layup.

Most studies in the literature reported the deformation (spring-in and warpage) decreases with increasing thickness [16][10][17][4][18][19][20][2][21][8][22][23][3]. This is expected because for a given geometry and layup, the laminate bending stiffness increases as thickness increases, making it harder to deform. Thicker laminates also better facilitate interlaminar shear, alleviating some residual stress and reducing deformation [24]. However, a few studies reported that laminate thickness has no influence on part deformation [11][25][7][14][9]. This could also be attributed to the narrow bandwidth of processing conditions in those individual studies. It is worth noting that a thick laminate exhibiting less deformation than a thin laminate does not necessary mean that the residual stress level is lower. Residual stress in the thicker laminates can lead to matrix microcracking.

The same recent meta-analysis mentioned in the effect of corner radius on RSDM above also corroborate that the bending stiffness coefficient (D_{22}), which captures the effect of both layup sequence and laminated thickness, can be used as a proxy for calculating spring-in [26][15]. Given a laminate thickness, the layup sequence that creates a higher bending stiffness will lead to less deformation. For example, for the same material and number of plies (laminate thickness), when varying the layup sequence for an L-shape, the deformation should follow: ± 45 > Quasi > cross ply 0/90 > UD 0 > UD 90.

The spring-in of UD [90]n parts is worth discussing. As mentioned, the fundamental driver for spring-in is the in-plane and through thickness strain difference. Since the properties in the in-plane (along the flange length) and through thickness directions of a [90]n laminate are both resin dominated and similar, the common understanding is that spring-in would be minimum for [90]n L-shape and C-shape specimens. However, non-negligible spring-in has been observed in [90]n specimens in literature. The discrepancies are attributed to tool-part interaction, through thickness cure, V_f gradient, or fiber misalignment. Thus, processing conditions and defects can also impact part deformation, especially in the case on UD [90]n parts, where the bending stiffness along the flange length direction is very low.

Effect of core and inserts on RSDM[edit | edit source]

Core material can significantly affect the through thickness strain as the composite part is being cooled from curing temperature. Thus the residual stress and deformation of a curved Sandwich Panels structure depends on the coefficient of thermal expansion of the constituents as well as the constraints between the core and the skin. Among which, the coefficient of thermal expansion of the core in through-thickness direction is very important[27]. Core and inserts can affect the flexural rigidity of the part, which plays an important role in deformation. In general, the thicker the core, the stiffer the parts, the more resistant it is to process induced deformation[28]. However, the effect of core thickness increase on reduced deformation is non-linear. Run-out geometry around the core may also affect process induced deformation.

Effect of part size on RSDM[edit | edit source]

Part size can also affect the part deformation, particularly due to warpage via tool-part interaction. Large acreage of flat parts or parts with mild curvature (such as a wing skin) are prone to this type of deformation. Part aspect ratio (length/thickness), processing pressure and surface condition, which affects the friction between the part and the tool are a few of the determining processing parameters. Although larger parts have been observed to warp more compared to smaller parts, regardless of processing conditions and part thickness[29]. Tool-part interaction is discussed in more details on Effect of tooling in a RSDM system.

Related pages

Page type	Links
Introduction to Composites Articles	
Foundational Knowledge Articles	
Foundational Knowledge Method Documents	
Foundational Knowledge Worked Examples	
Systems Knowledge Articles	• Effect of equipment in a RSDM system - A278 • Effect of shape in a RSDM system - A276
Systems Knowledge Method Documents	
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Systems Catalogue Objects – Material	
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Case Studies	
Perspectives Articles	• Composites Process Simulation: A Review of the State of the Art for Product Development - A283

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About **Help**

Engineered materials (designed to have specific properties) made from two or more constituent materials with different physical or chemical properties. The constituents remain separate and distinct on a macroscopic level within the finished structure.

The continuous material phase that binds the reinforcement together, maintains shape, transfers load, protects the reinforcement from environment and damage, and provides the composite support in compression.

Desirable characteristics:

- Moisture/chemical resistance
- Low density
- Processability

For polymer matrix composites (PMCs), resin refers to the matrix; the continuous material phase that binds the reinforcement together, maintains shape, and transfers load. Resins are divided into two main groups: thermosets and thermoplastics.

A laminate whose in-plane shear coupling stiffness is zero. This occurs if all plies in a laminate that are not oriented parallel or perpendicular to the primary laminate axis (i.e. non 0 or 90 degree plies) occur only in $\pm\theta$ pairs that have the same thickness and elastic properties.

Thermosets are a class of polymer that undergo polymerization and crosslinking during curing with the aid of a hardening agent and heating or promoter. Initially they behave like a viscous fluid. During curing, they change from viscous fluid to rubbery gel (viscoelastic material) and finally glassy solid.

If heated after curing, initially they become soft and rubbery at high temperatures. If further heated, they do not melt but decompose (burn)

Comes in two parts: part A (resin) and B (hardener). When mixed, curing reaction starts and is not reversible.

Examples include epoxy or polyester.