Mold Development for Resin Transfer Molding with Dimension Variation and Deformation Compensation

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Abstract. A method for achieving better dimensional control for composites based on deformation compensation in mold design is presented in this paper. The process-induced deformation of a general angled part, i.e. spring-in, was studied statistically to account for the processing-related uncertainties. The part geometry was modified based on the results from the statistical analysis for offsetting the deformation. The modified part geometry was used to design the mold for resin transfer molding and the mold was made by the CNC wire electrical discharge machining (WEDM) process. Five sample parts were fabricated using the mold and the spring-in angles were measured. The results show that the process-induced deformation is significantly reduced through deformation compensation. This method presented in this paper provides an approach to minimizing the overall process-induced deformation of resin transfer molded parts.

Introduction

Fiber-reinforced composites are a class of widely used engineering material. The low density, high strength, high stiffness to weight ratio, excellent durability, and design flexibility of composites are the primary reasons for their use in many structural components in aircraft, automotive, marine, and other industries [1]. Despite all these advantages, composite materials have not been as widely used as expected because of the complexity and cost of manufacturing. One of the main problems is poor dimensional control. Deformation is induced due to the fiber-resin CTE mismatch and the curing shrinkage of resin.

Past research on the process-induced deformation of composites was mainly focused on the spring-in of angled parts, i.e. the reduction in the enclosed angle. The spring-in of composites was either studied by elastic [2] or viscoelastic [3] models. Despite these studies on spring-in, dimensional control of composites has been primarily relying on trial-and-error approaches. The disadvantage is the high cost of mold modification. Capehart et al. [4] employed an iterative algorithm for designing corrective mold for open mold composite body panels. The difficulties of correcting deformation in mold design include inaccurate prediction of deformation and uncertainties existing in composites processing.

This study aims to deliver a method for better dimensional control for composites manufacturing. The process-induced deformation of a general angled part, i.e. spring-in, was studied statistically to account for the processing-related uncertainties. The part geometry was modified based on the results from the statistical analysis for offsetting the deformation. The modified part geometry was used to design the mold for resin transfer molding and the mold was made by the CNC wire electrical discharge machining (WEDM) process. Five sample parts were fabricated using the mold and the spring-in angles were measured.

Calculation of Spring-in

An angled part as shown in Fig. 1 was studied as an example to illustrate this method. Because of its constant cross-section, the part is studied in 2-D and the spring-in was calculated using the effective CTE [5].

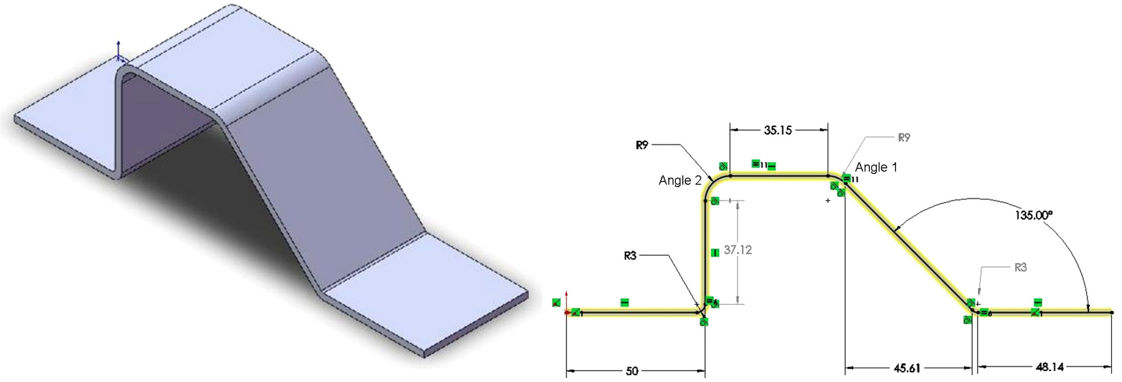

Fig. 1: Angled composite part

The part is made from E-glass fibers and epoxy resin, and the relevant properties and CTE are shown in Table 1. The stacking sequence is $[0/90]_{3s}$ and the nominal fiber volume fraction is 50%.

Table 1: Material properties of E-glass fibers and epoxy resin in the glassy state [1]

E-glass fibers	E_f **(GPa)**	ν_f	α_{fL} **(μm/m/°C)**
	72	0.2	5
Epoxy	E_m **(GPa)**	ν_m	α_m **(μm/m/°C)**
	2.581	0.265	64

Given these constituent properties and the fiber volume fraction, the lamina properties, including the longitudinal modulus E_{11}, transverse moduli E_{22} and E_{33}, and shear moduli G_{12}, G_{13} and G_{23}, are derived by Hashin's model [6], and the stiffness matrix for a lamina $\overline{\mathbf{C}}$ is derived.

Another important aspect is that resin will undergo substantial shrinkage. In the beginning of a typical liquid composite molding process, resin is fully uncured and behaves as viscous fluid. During curing process, resin is heated up to an elevated temperature usually above T_g. A significant increase in modulus and decrease in specific volume begin to occur. Approximately 60% of the total volumetric shrinkage occurs prior to the gel point. Thus, only a small fraction of curing shrinkage contributes to the residual stress and warpage development. In this study, the volumetric curing shrinkage of epoxy in the glassy state was assumed to be 0.6%. This volumetric shrinkage is converted to linear shrinkage by

$$L_s \approx V_s / 3 \tag{1}$$

and is added to the CTE of epoxy, i.e.

$$\alpha_m^e = \alpha_m + \frac{V_s}{3\left(T_g - T_0\right)} \tag{2}$$

For this cross-ply laminate, the effective CTE and spring-in from calculation are: α_I = 14.39 μm/m/°C; α_T = 51.49 μm/m/°C; and $\Delta\phi = -0.437°$.

During the manufacturing of composites, uncertainties arise and these uncertainties cause part-to-part variations. Two notable aspects are: 1) fiber volume fraction can vary as much as 2-4% [7]; and 2) ply angle can vary as much as 2°. For this reason, the effective CTE and spring-in were studied statistically as shown in Fig. 2. With the assumption of normal distributions, the standard deviations of fiber volume fraction and ply angle were assumed to be 0.01 and 1°, respectively.

The effective CTE and spring-in were studied by a Monte Carlo method. 1000 fiber volume fraction and ply angle data were randomly generated and the corresponding effective CTE and spring-in were calculated. The distribution of spring-in is shown in Fig. 3.

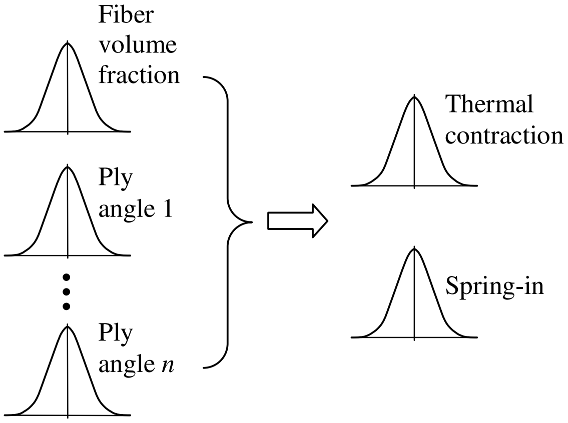

Fig. 2: Statistical analysis

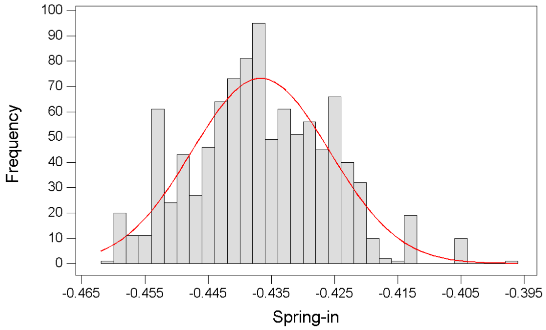

Fig. 3: Statistical distribution of spring-in

These statistical distributions are approximated by normal distributions based on the Anderson-Darling normality test [8]. The means and standard deviations are shown in Table 2. These statistical distributions give us flexibilities in offsetting process-induced deformation. The lower bound, average or upper bound can be chosen depending on the application requirements. In this study, the average values were chosen for deformation compensation.

Table 2: Mean and standard deviation of effective CTE and spring-in

	Mean	Standard deviation
In-plane CTE (μm/m/°C)	14.39	0.23
Through-thickness CTE (μm/m/°C)	51.47	1.15
Spring-in (°)	-0.44	0.01

Deformation Compensation

Once the distributions of effective CTE and spring-in are derived, process-induced deformation can be offset through mold design. In order to offset process-induced spring-in, enclosed angles need to be enlarged. The enclosed angle after angular compensation is given by

$$\phi = 180\frac{(\alpha_I - \alpha_T)\Delta T}{1+\alpha_I \Delta T} + \phi_{nom}\frac{1+\alpha_T \Delta T}{1+\alpha_I \Delta T} \tag{3}$$

where ϕ = enclosed angle after angular compensation; and ϕ_{nom} = nominal enclosed angle.

For this angled part, the spring-in angles of 90° and 135° enclosed angles are 0.44° and 0.22°, respectively. The corresponding enclosed angles after angular compensation are 90.44° and 135.22°, respectively.

The dimensions after angular compensation are shown in Fig. 4. The molds were designed using the mold design module of SolidWorks and made by the CNC WEDM process. The complete mold assembly is shown in Fig. 5.

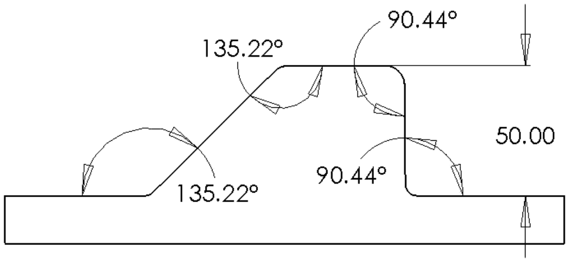

Fig. 4: Dimensions after linear and angular compensation

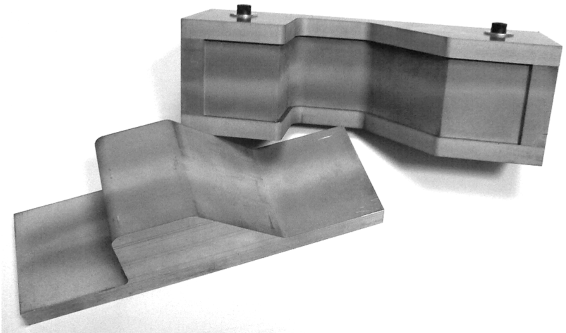

Fig. 5: Finished molds

Experiment Validation

In order to validate this approach, five parts were made using this mold set from glass fiber mats and EPON828 resin. After fabrication, these parts were measured by a coordinate measuring machine and the corresponding enclosed angles were found. The results are shown in Table 3. It is seen that the spring-in has significantly reduced.

Table 3: Enclose angles of fabricated parts

Part	Angle 1 (135°)	Angle 2 (90°)
1	135.07	90.02
2	135.04	90.01
3	135.08	90.13
4	135.07	89.99
5	135.01	90.10

Conclusions

Because composites processing is a net-shape process, in order to reduce or eliminate the deformation induced in the manufacturing process, molds need to be modified to offset the deformation. However, uncertainties exist in the processing of composites, and these result in the uncertainty of the spring-in angle and thermal expansion. Thus, these uncertainties need to be taken into account. In this study, the process-induced deformation of a general angled part, i.e. spring-in, was studied statistically to account for the processing-related uncertainties. The part geometry was modified based on the results from the statistical analysis for offsetting the deformation. The modified part geometry was used to design the mold for resin transfer molding and the mold was made by the CNC WEDM process. Five sample parts were fabricated using the mold and the spring-in angles were measured. The results show that the process-induced deformation is significantly reduced through deformation compensation. This method presented in this paper provides an approach to minimizing the overall process-induced deformation of resin transfer molded parts.

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