RESIDUAL STRESS, SPRING-IN AND WARPAGE IN AUTOCLAVED COMPOSITE PARTS

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SUMMARY: This paper presents an overview of residual stress build-up and shape distortions in autoclaved composite laminates. It discusses the sources of stress build-up and shape distortions and presents experimental results that identify parameters that drive shape distortions. It is shown that spring-in is mainly driven by volume changes due to thermal and cure shrinkage effects, whereas warpage of symmetric laminates is driven by mechanical tool-part interaction, which is sensitive to variations in the process conditions.

KEYWORDS: residual stress, processing, spring-in, warpage, tooling

INTRODUCTION

Residual stresses are inevitably generated within polymer matrix composites during processing. The sources of residual stress can be classified as intrinsic (related to material, lay-up, and part shape) or extrinsic (related to processing and tooling). This classification allows sources related to material selection and part design to be separated from sources that are controlled by processing. In thermoset polymer matrices, the material related sources of residual stress are thermal volume changes of the matrix and fibres, and cure shrinkage of the matrix. The extrinsic sources of residual stresses depend on the details of the process and include mechanical tool-part interaction and residual stress build-up due to cure gradients during processing. Although there are many similarities between different processes in this respect, this paper is focused on stress build-up and shape changes in autoclaved composite parts.

RESIDUAL STRESS

Residual stresses can build up on three different length scales in composites: fibre-matrix, lamina-laminate, and structural scales. Residual stresses at the fibre-matrix level are often not considered explicitly in the design of composites; frequently they are absorbed as hidden knock-down factors on the strength properties of the material [1]. The calculation of processing residual stresses at the fibre-matrix level has received much less attention than higher level calculations to date; Ciazzo et al [2] is an example of some recent preliminary work at this length scale. Residual stresses on the lamina-laminate and structural levels are more readily calculated, often using laminate plate theory or finite element analysis.

Intrinsic sources generate residual stress at the constituent level and the effect is integrated up through the length scales. Extrinsic sources generate stress at the boundaries of the structure and the effect is migrated down through the lengths scales. Thus intrinsic sources act from the "inside and outwards" and extrinsic sources act from the "outside and inwards". Intrinsic sources have in general the largest effect on fibre-matrix level stresses and extrinsic sources have the largest effect on the structural level stresses (Figure 1). The main effects of residual stress are a reduction in strength, and shape distortion. Stresses at the fibre-matrix, lamina-laminate, and structural levels all affect the strength of the component, whereas only lamina-laminate and structural level stresses affect dimensional fidelity to any significant degree. Figure 1 shows a schematic of the relationship between the source of stress, the length scale at which it is acting, and the effect of that stress.

The magnitude of residual stresses and their effect on strength and shape distortions are in many cases not easily calculated. To date, not all sources for residual stress build-up have been identified and quantified; for example mechanical tool-part interaction is not well understood, and even the constitutive behaviour of a curing composite is still an active area of research. There have been significant advances in this area [e.g. 3, 4, 5, 6] but accurate and reliable predictions are beyond standard engineering practice today.

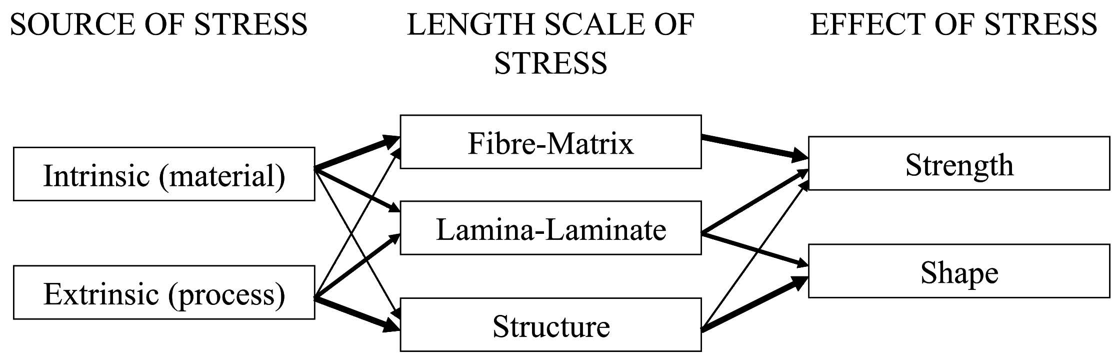

Figure 1. Schematic of the relationship between stress source, length scale of stress, and the effect of residual stress. Thicker arrows indicate a stronger relationship.

Figure 2a shows a typical cure cycle for a thermoset composite, where the approximate material behaviour is indicated in italics. Before gelation the matrix is viscous and no residual stresses can be carried by the matrix. After gelation, the matrix is a rubbery visco-elastic solid with very short relaxation times. At the end of the final temperature hold, the matrix is fully cured and behaves as a visco-elastic glassy solid with a very long relaxation time (Figure 2b). The majority of the residual stress is generated during the cool-down from the final hold temperature. These stresses are the easiest to predict as the material can be treated as being thermo-elastic with fairly good accuracy. Stresses built up earlier in the cure cycle, for example due to cure shrinkage and tool-part interaction, are more difficult to estimate.

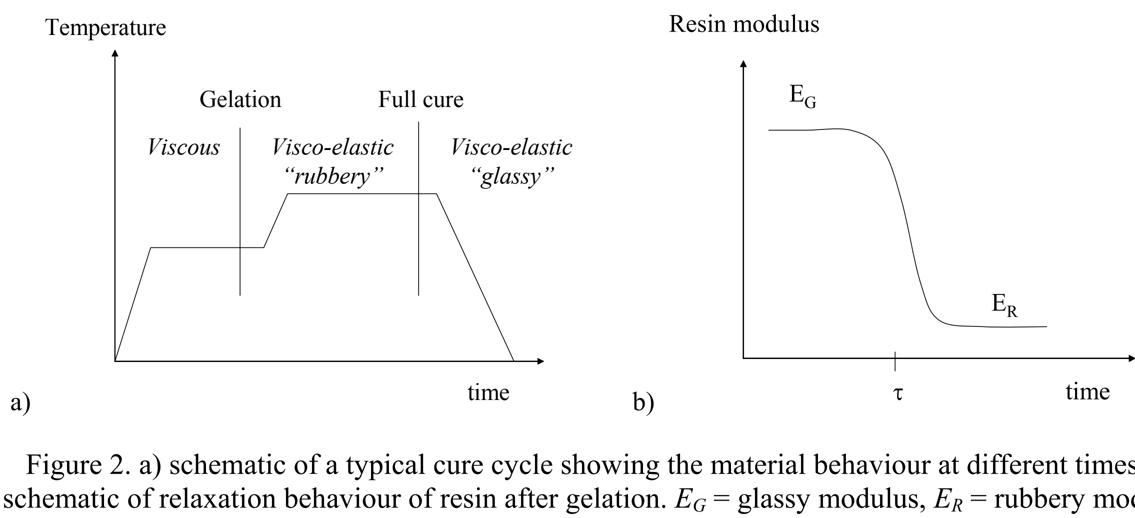

Figure 2. a) schematic of a typical cure cycle showing the material behaviour at different times; b) schematic of relaxation behaviour of resin after gelation. E_G = glassy modulus, E_R = rubbery modulus, τ = characteristic relaxation time.

The incremental stress build-up $\Delta\sigma(t)$ due to a strain increment $\Delta\varepsilon(t)$ at time t in a hardening material such as a curing composite can be approximated as [4]

$$\Delta\sigma(t) = E(t)\Delta\varepsilon(t) \tag{1}$$

where $E(t)$ is the modulus of the material when the mechanical strain increment $\Delta\varepsilon(t)$ is applied. For this formulation to work, the modulus $E(t)$ in eq. (1) has to be the relaxation modulus at a representative time scale of the process. It has been reported that the glassy and rubbery modulus of a curing resin is relatively insensitive to the degree of cure of the material [6]. What changes with the degree of cure is the characteristic relaxation time τ (Figure 2b). This means that the "effective" modulus at time t is the rubbery modulus E_R if relaxation times are very short, as in the case of low degrees of cure, or the glassy modulus E_G if relaxation times are very long, as in a fully cured vitrified polymer. As the resin is curing, the effective modulus changes with time from the rubbery modulus to the glassy modulus. Eq. (1) shows that mechanical strains applied to the composite early in the cure cycle have a significantly smaller effect than strains applied late in the cycle due to the large difference in the rubbery and glassy modulus.

SPRING-IN

Spring-in is defined here as a reduction of closed angles due to process-induced stresses or strains. Spring-in is a fairly well studied phenomenon [7, 8, 9, 10, 11, 12] and for an anisotropic material with the simple curved geometry shown in Figure 3, given a longitudinal strain ε_l and a transverse strain ε_t, the spring-in angle $\Delta\theta$ is given by eq. (2).

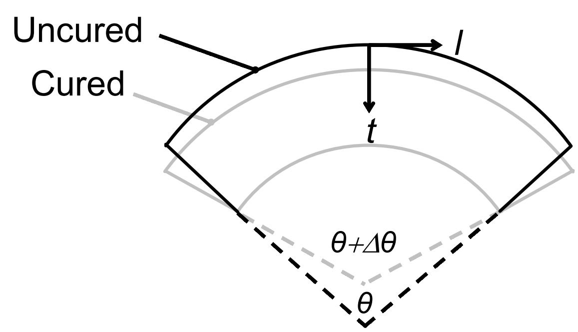

Figure 3. Geometry of spring-in of an enclosed angle.

If the sources of the longitudinal and transverse strain are thermal expansion $\alpha\Delta T$ and cure shrinkage ϕ, the spring-in angle can be calculated as [13]

$$\Delta\theta = \theta\left(\frac{\varepsilon_l - \varepsilon_t}{1+\varepsilon_t}\right) = \Delta\theta_{CTE} + \Delta\theta_{CS} = \theta\left(\frac{(\alpha_l - \alpha_t)\Delta T}{1+\alpha_t\,\Delta T}\right) + \theta\left(\frac{\phi_l - \phi_t}{1+\phi_t}\right) \tag{2}$$

where subscripts l and t refer to the longitudinal and transverse directions respectively. $\Delta\theta_{CTE}$ and $\Delta\theta_{CS}$ are the contributions from thermal and cure shrinkage effects, respectively.

The thermal component of spring-in arises mainly during cool-down from the final hold temperature. If the composite component is constrained from deforming because of the tool, lamina-laminate and structural level residual stresses will develop instead. These stresses will be relieved when the component is removed from the tool, and the part will spring in. As this occurs when the part is essentially thermo-elastic, there is no difference in the resulting spring-in if the part is free to spring-in or constrained by the tool during cool-down. The situation is quite different for strains generated before the part is fully cured. Cure shrinkage gives a similar strain state compared to a thermal cool-down. If a component is processed without a tool and is free to deform during cure, the full cure shrinkage strains will result in spring-in as shown in eq. (2). However, if the component is constrained from deforming by the tool, the cure shrinkage strains will cause residual stress development in proportion to the effective modulus of the material when the shrinkage occurred, as shown by eq. (1). This residual stress will cause spring-in when the part is removed from the tool, but since the Young's modulus of the fully cured part is higher, the resulting deformation will be lower. Thus a component that is constrained from deforming during cure will exhibit less spring-in than a component that is free to deform, due to cure shrinkage strains. The effect of strains occurring during cure on the final stress and deformation of the component is scaled by the ratio of the effective modulus when the strain occurred and the final modulus of the component. This means that although the total volumetric cure shrinkage often is substantially greater than the thermal volume changes, the fact that cure shrinkage mostly occur when the modulus is very low leads to a reduced effect on residual stresses. In view of this, the values used for cure shrinkage strains in the second term of eq. (2) must be chosen with care if the component is prevented from deforming during cure by the process tool.

Equation (2) is a simple and useful formula that accounts for the intrinsic sources of spring-in: thermal expansion and cure shrinkage. The accuracy of eq. (2) can be evaluated by comparing it against experimental data. A larger study examining the effect of extrinsic parameters on spring-in and warpage of autoclaved parts has been undertaken [14]. The extrinsic parameters studied were: part shape (C or L), lay-up, flange length, part thickness, part angle, tool material, tool surface, and cure cycle. Figure 4 shows a comparison of experimentally measured spring-in and predicted spring-in using eq. (2). The figure shows the spring-in prediction based only on the thermal component, $\Delta\theta_{CTE}$ (solid line), and the prediction including both thermal and cure shrinkage components, $\Delta\theta_{CTE} + \Delta\theta_{CS}$ (dashed line). The input data for the prediction of the thermal component are the longitudinal and transverse components of thermal expansion for the fully cured material. The input data for the cure shrinkage component is more arbitrary and was based on the assumption that 2% of resin volumetric shrinkage contributes to spring-in when the resin is in its glassy state [14]. Spring-in, which is a corner phenomena, is often confounded by warpage of the sections emanating from the corner. The data presented in Figure 4 represents the spring-in right at the corner after the effect of flange warpage is subtracted [14].

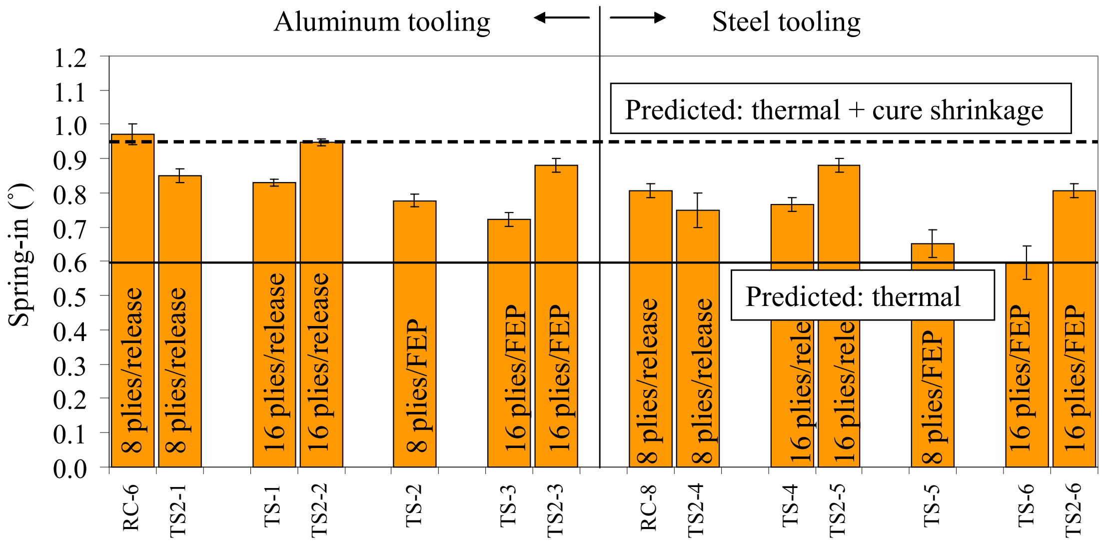

Figure 4. Comparison of measured and predicted spring-in. Dashed and solid lines represent analytical predictions using Eq. (2), with and without cure shrinkage, respectively [14]. All parts had an enclosed angle θ of 90° and were cured using a two-hold cycle.

Figure 4 shows that that the experimental data is well bounded by the two predictions. It also shows that the extrinsic parameters studied, part shape (C or L), lay-up, flange length, part thickness, and part angle, tool material, tool surface, and cure cycle, have little effect on spring-in. Thus spring-in appears to be mainly driven by thermal and cure shrinkage effects as described by eq. (2).

WARPAGE

Warpage is here defined as a deviation from flatness of initially flat laminates due to process-induced stress or strain. In symmetric and balanced laminates, warpage typically arises because of non-uniform properties through the thickness, such as fibre volume fraction gradients [12], or mechanical tool-part interaction [15,16]. When parts are processed on a tool material with a high coefficient of thermal expansion, plies close to the tool-part interface may get stretched, which causes a stress gradient through the thickness that locks in when the part cures. As a result, these parts warp away from the tool after processing, as shown in Figure 5. The results presented here are for T800H/3900-2 UD prepreg laminates processed under no-bleed conditions on aluminum tooling coated with release agent and a release sheet of Fluorinated Ethylene Propylene under 586 kPa autoclave pressure [16]. Properties were uniform through the thickness, and thus the warpage was due to mechanical tool-part interaction. Figure 5 shows an example of warpage due to tool-part interaction of nominally flat 4-ply unidirectional carbon/epoxy parts of various lengths.

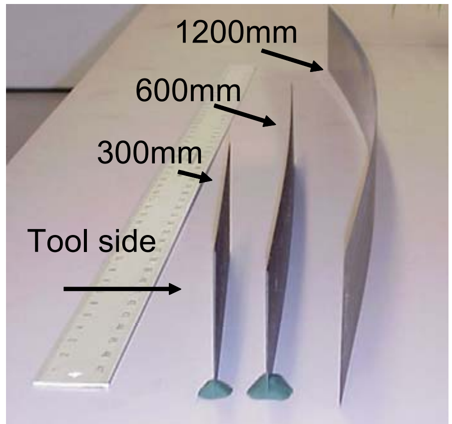

Figure 5. Photograph showing the warpage due to tool-part interaction of nominally flat 4 ply unidirectional carbon/epoxy parts of various lengths. Parts were processed on aluminum tooling coated with release agent and a Fluorinated Ethylene Propylene sheet under 586 kPa (85 psi) autoclave pressure [16].

Warpage results from two independent studies will now be compared: the results from [14] are called study A here, and the results from [16] are called study B. Together, these studies examine the effect of several extrinsic variables on warpage. Both studies use the same material: uni-directional (UD) T800H/3900-2 carbon/epoxy prepreg made by the Toray Company. The parameters studied and their ranges are shown in Table 1. In both studies, warpage was measured using optical non-contact techniques. For details of specimen preparation, process conditions, and warpage measurements refer to [14, 16].

Table 1. Parameters and ranges used in warpage studies A [14] & B [16].

Parameter	**Study A**	**Study B**
Part length (mm)	160-190	300 – 1200
Part thickness (plies[1])	8 or 16	4, 8, or 16
Lay-up[2]	UD, quasi-isotropic	UD
Tool material	Steel, aluminum	Aluminum
Tool surface treatment[3]	Release agent, FEP release sheet	Release agent, FEP release sheet
Cure cycle[4]	1 or 2 holds	1 hold
Autoclave pressure (kPa)	586	103, 586

1) 1 ply = 0.2 mm
2) UD = all fibres in the length direction of the laminate
3) Freekote 700 NC release agent was applied in three layers
4) Temperature ramp rate 2C/min. 2-hold cycles had an intermediate hold at 135C for 140 min. Final hold at 180C for 120 min for both cycles.

Figure 6 and Figure 7 show the measured warpage from the two studies. Warpage is presented in terms of the dimensionless warpage *k*t* where curvature *k* is multiplied with the laminate thickness *t*.

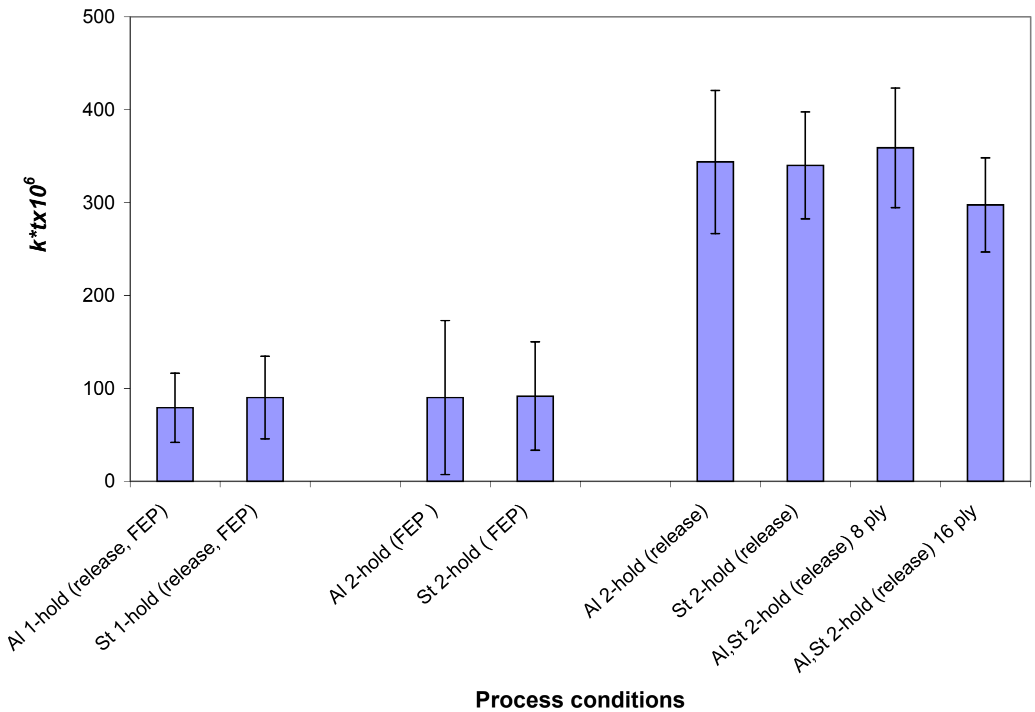

Figure 6. Dimensionless warpage *k*t* from study A. Solid bars denote mean values and error bars +/- one standard deviation.

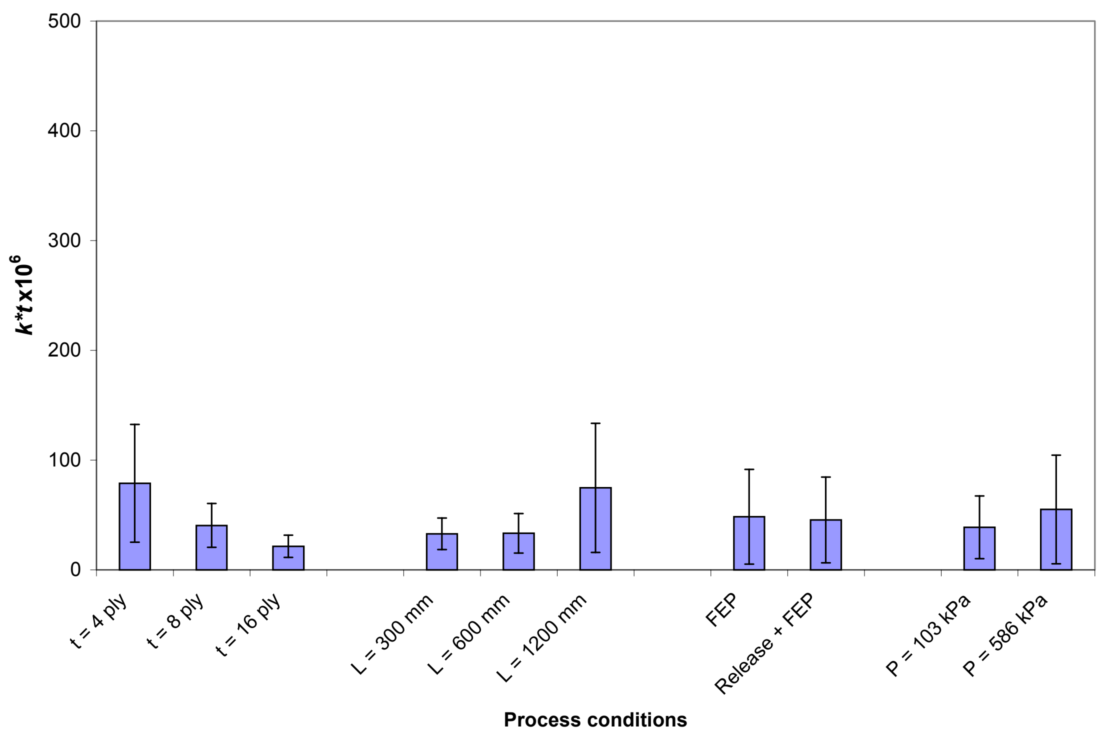

Figure 7. Dimensionless warpage *k*t* from study B. Solid bars denote mean values and error bars +/- one standard deviation.

Figure 6 shows that the warpage is smallest when 1-hold cycles are used. The warpage is also not sensitive to variations in the other parameters of tool material, lay-up, tool surface conditions, part length and thickness, when 1-hold cycles are used. When 2-hold cycles are used, there is a large difference in the measured warpage if a FEP release sheet is used between the part and tool in addition to the release agent. When a FEP sheet is used, the warpage behaviour is similar to that for 1-hold cycles. In the absence of a FEP sheet, the warpage increases by a factor of four. The magnitude of warpage for this cure cycle is relatively insensitive to variations in the other process parameters: tool material, lay-up, part length and thickness. Warpage appears to decrease slightly with increasing laminate thickness but the results are not statistically significant given the variability in the data.

Figure 7 shows that the dimensionless warpage $k*t$ is less than $1*10^{-4}$ in all cases in study B, which is similar to specimens cured with a 1-hold cycle in study A. There is a clear trend with decreasing warpage with increasing part thickness and decreasing part length. The tool surface conditions have little effect and there is a slight increase in warpage with increasing autoclave pressure. Table 2 shows a summary of the effect of different extrinsic parameters on warpage in studies A and B.

Table 2. Summary and comparison of the effect of extrinsic parameters on the dimensionless warpage $k*t$ in studies A and B.

Parameter	**Study A**	**Study B**	**Agreement/Disagreement**
Part length	No significant dependence	Longer warps more	Results from study A not conclusive as length changes were less than 20%
Part thickness	Slight dependence: thinner laminates warps more	Thinner laminates warp more	The two studies agree
Lay-up	No dependence		
Tool material	No dependence		
Tool surface treatment	No difference for 1-hold cycles but large difference for 2-hold cycles	No dependence	The two studies agree
Cure cycle	2-hold gives much more warpage than 1-hold if there is no release film		
Autoclave pressure		Slight dependence: higher pressure gives more warpage	

When comparing the results from the two studies agreement in the warpage behaviour is found. The observation that the cure cycle has a large effect on warpage only with 2-hold cycles where there is no FEP release sheet between the part and tool is strong evidence that the observed warpage is indeed caused by mechanical tool-part interaction.

DISCUSSION AND CONCLUSIONS

This study showed that spring-in is largely driven by intrinsic sources, i.e., volume changes due to thermal and cure shrinkage effects. Extrinsic parameters, e.g. processing and tooling was seen to have little effect on spring-in. The amount of spring-in due to thermal volume changes can readily be calculated using a simple equation, eq. (2). The same equation can also be used to account for cure shrinkage of the resin but the required shrinkage parameters are difficult to estimate as shrinkage occurs while the resin is hardening.

Warpage of flat symmetric laminates is not caused by volume changes of the material but by mechanical tool-part interaction in the current case. The data showed that parts cured with a one-hold cycle exhibited a dimensionless curvature $k*t$ of the order of 10^{-4}. Parts cured with a two-hold cycle, without a FEP release sheet between the part and tool, had four times as much warpage. Parts cured with a one-hold cycle gelled at the end of the temperature hold. The data indicate that despite the resin being liquid on heat-up, stresses build up in the laminate during heat-up. These stresses are locked in when the part gels and hardens on the temperature hold. This mechanical interaction between the tool and the part very early in the cure cycle has been verified with strain gauge measurements [16]. In the current study, a 0° ply was at the tool-part interface for all lay-ups. Another study has reported that by placing a 90° ply at the tool-part interface, warpage is virtually eliminated [17]. The two-hold cycle used was designed such that the resin gelled at the end of the first temperature hold. The material is thus in its solid state during heat-up to the final hold temperature. Figure 6 shows that there is a significant increase in warpage in this case unless a FEP release film is used between the part and tool to decouple the two mechanically.

Warpage is an elusive manufacturing problem that often appears unexpectedly in industry. There has, however, been a substantial increase in the understanding of the causes and effects of process-induced warpage in the community in the past decade and we are close to having the requisite physical understanding of the problem to be able to develop computational tools and models to predict this phenomenon.

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