THE EFFECT OF TOOLING MATERIAL, CURE CYCLE, AND TOOL SURFACE FINISH ON SPRING-IN OF AUTOCLAVE PROCESSED CURVED COMPOSITE PARTS

Göran Fernlund and Anoush Poursartip

Department of Metals and Materials Engineering, The University of British Columbia
309-6350 Stores Road, Vancouver, B.C., Canada, V6T 1Z4

SUMMARY: The purpose of this paper is to demonstrate the effect that the tooling material, the tool-surface condition, and the cure cycle can have on the spring-in of curved composite laminates. A set of experiments was performed with T800H/3900-2 carbon/epoxy composite C-channels made on aluminum tooling with different surface treatments and cured using both single-hold and double-hold cure cycles. The experiments were also simulated using the composites process modelling software COMPRO. Measurements of flange spring-in on the manufactured C-channels showed that the spring-in varied as much as a factor of two between the different specimens, and that there is a complex interaction between flange spring-in and the tooling material, the tool surface treatment, and the cure cycle. The predictions of flange spring-in from COMPRO was found to be about 20% too high in general, but all the observed trends were accurately predicted.

KEYWORDS: Spring-in, autoclave processing, deformations, modelling, finite element analysis, COMPRO

INTRODUCTION

The anisotropic nature of fibre-reinforced polymer matrix composite materials often causes residual stress build-up during processing, and subsequent warpage of the composite part when it is removed from the mould. The relaxation of residual stresses often cause flat sections to warp and enclosed angles to "spring-in". In high performance applications such as in the aerospace industry, process induced warpage needs to be compensated for when designing the tool to avoid problems with fit-up in the assembly of the aircraft. Because of a strong aversion to introducing stresses in the structure during assembly, the clamp-up forces allowed to join up different parts are usually very small. This means that even a little warpage and spring-in can have severe implications in assembly.

During processing of polymer matrix composites, residual stresses often develop both on the fibre-matrix level and on the ply or laminate level. With respect to process-induced warpage, only stresses and stress gradients on the ply or laminate level are of interest. The difference in the thermal expansion in-plane and out-of-plane, and cure shrinkage of the resin, are the main driving forces behind residual stress build-up and subsequent warpage of polymer composite parts [1-3]. Both these phenomena will cause curved composite laminates to warp, and there are simple formulas that predict the warpage or spring-in of curved composite laminates available in the literature [6,7]. These simple formulas give good predictions in certain cases, but there are often other factors that come into play as will be shown in this paper. There has been work done to develop more sophisticated analytical and numerical models to predict the residual stress development in cured composite parts. These models range from one-dimensional analysis [8,9], two-dimensional analysis [10,11], to three-dimensional analysis [12]. However, there are more factors than anisotropic thermal expansion and resin cure shrinkage that affect the residual stress build-up and subsequent warpage of composite parts made in an industrial setting. In an attempt to address this, the Composites Group at the University of British Columbia has developed COMPRO, a finite element based composites process modelling software that simulates the physics, chemistry and mechanics of the autoclave process [4,5]. The software was developed in close collaboration with The Boeing Company (Seattle) and is intended to include industrially relevant effects such as autoclave and tool characteristics, as well as the material behaviour and material property development during cure. COMPRO time-steps though the cure cycle and determines component internal temperature, resin degree of cure, resin flow and the development of residual stresses and deformations, among other things. The following section gives a brief overview of how process analysis and process modelling is performed using COMPRO.

PROCESSING MODELLING USING COMOPRO

COMPRO is a two-dimensional finite element based software for the analysis of the autoclave process. The details of the software and the underlying science has been described elsewhere [4,5]. The software has a user-friendly visual interface and runs on the Windows 95/98/NT platform. The following main steps are involved in process analysis using COMPRO.

1. Generate Finite Element Mesh Of Tool And Part (2-D Cross-Section)

It is easiest to start with a CAD file af a cross-section of the tool and part geometry that is to be analyzed, and use a commercial finite element pre-processor to generate a finite element mesh of the assembly. COMPRO has a built-in mesh generator for simple geometries, and supports the commercial pre-processors: PATRAN, MARC Designer, and HyperMesh for meshing of more complex geometries. Bagging materials, breathers, bleeders, caul-sheets, and other materials that are believed to affect the curing of the composite part should be included in the mesh. Figure 1 shows how the COMPRO interface looks like. The mesh in the figure represents a cross-section of a carbon/epoxy wing spar with a Nomex honeycomb core in the web. Note that the tooling is included in the mesh.

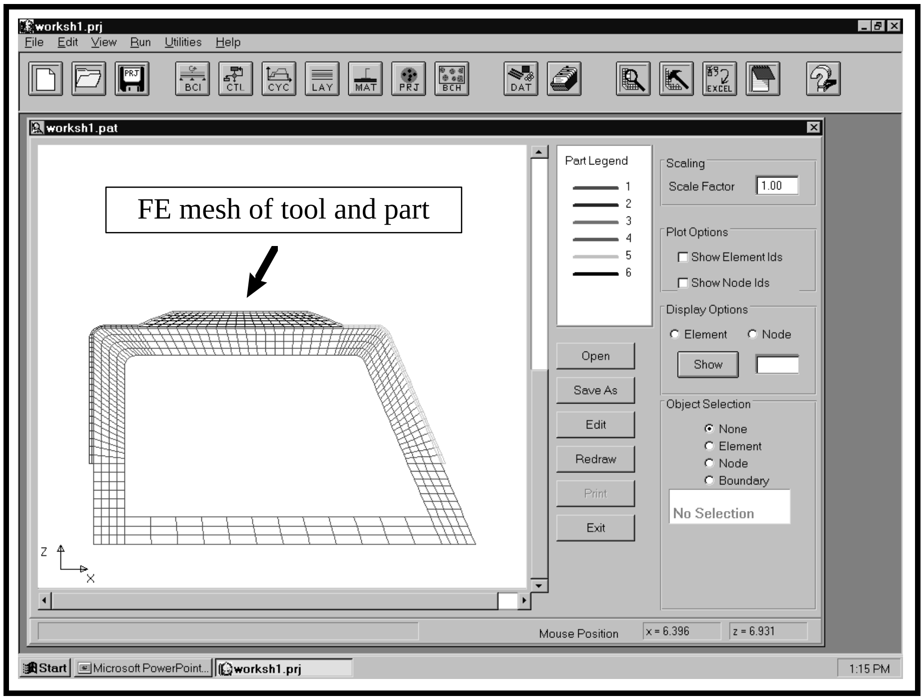


Figure 1. COMPRO interface showing a finite element mesh of a composite wing spar and tooling cross-section.

2. Model Set-Up

By using icons and pull-down menus in standard Windows fashion, the model is defined and prepared for execution by entering process parameters in text boxes. The user specifies the cure cycle, the material properties, and other relevant process parameters, and defines the type of process control used together with the locations of controlling thermocouples. Tool materials, composite materials, cores, inserts, and bagging material are defined as required. The material properties for curing composite materials are fairly extensive and need to be characterized before hand. Material properties for most non-curing materials such as metal tooling can be taken from handbooks. COMPRO has an internal database with material properties for a few prepreg materials used in the aerospace industry. The model also allows the user to input data about the heat-transfer characteristics of the autoclave used to cure the part.

3. Run Model And Analyze Results

A COMPRO simulation gives a wealth of information about the process during the cure cycle – often more than you know what to do with. A few examples of the output at specific times of the process are shown in the following figures. Figure 2 shows the predicted temperature profile in the part and tool during heat-up. Figure 3 shows the in-plane strains in the part and tool at the end of the cure cycle, before tool removal. Figure 4 shows the final part shape and flange spring-in due to residual stress build-up. These are examples of the spatial variation of different internal process variables at different times in the process. The temporal variation of the process variables is best studied using a spread-sheet software such as Microsoft Excel.

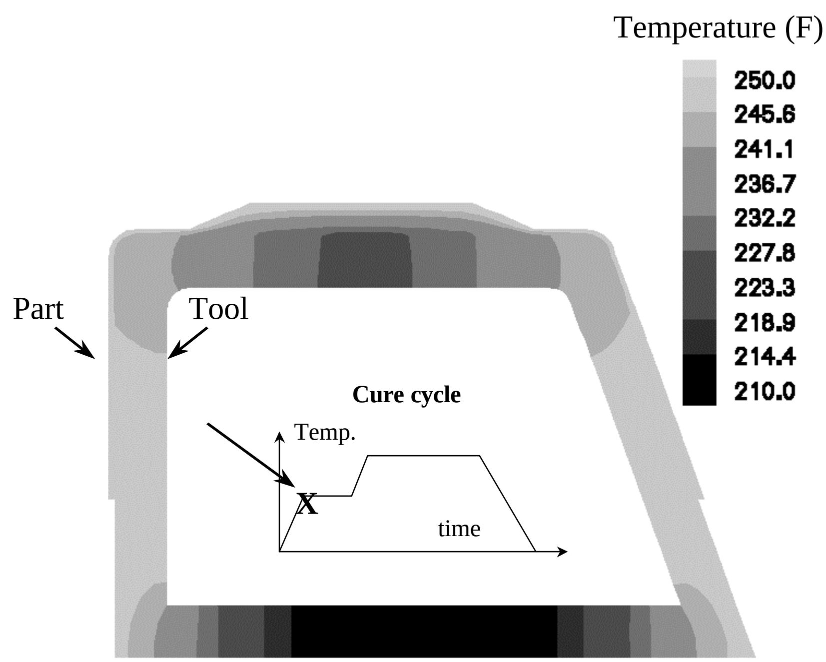


Figure 2. Temperature profile in the part and tool during heat-up.

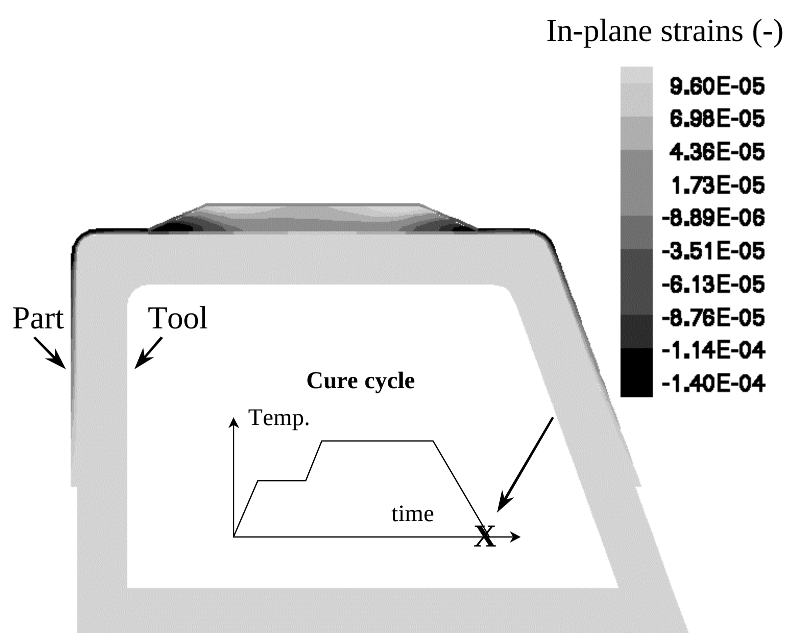


Figure 3. Residual strains in the part and tool before tool removal (these residual strains will cause warpage of the part when removed from the tool).

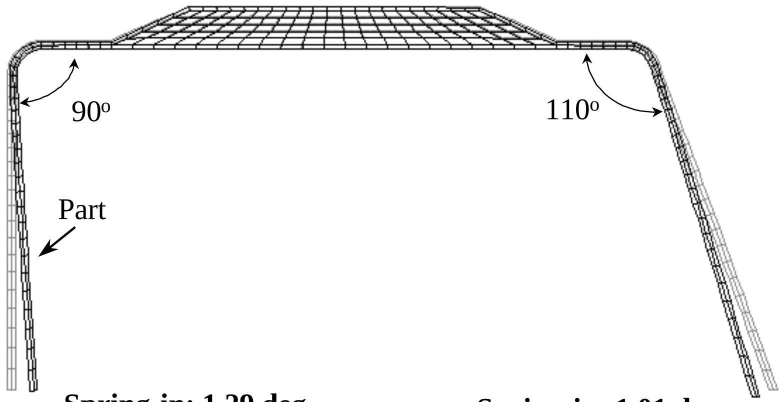


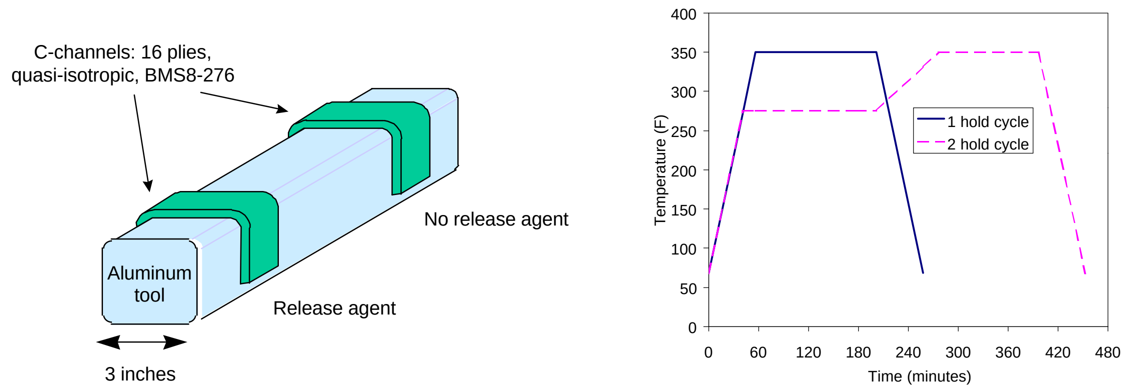
Figure 4. Final part shape and flange spring-in due to residual stress build-up during cure.

TOOLING, CURE-CYCLE, AND SPRING-IN

Two factors that often are assumed to have little or no effect on the dimensional fidelity of composite parts are the tooling and the cure-cycle. Tool design is often based on past experience and rules of thumb. The tool designer tries to find a good compromise between seemingly contradictory requirements: low cost, high durability, low thermal expansion, high operating temperature, high stiffness, and low thermal mass. Although there is a considerable amount of empirical knowledge in industry that can guide a designer in a qualitative way, a good understanding of the underlying science is lacking – why do some tooling concepts work in certain cases but not in others?

Cure cycle recommendations for different resin and prepreg systems are often given by the material suppliers. In addition, most composite part manufacturers have internal processing specifications that they have to follow. In reality, even if parts are processed within the specifications, there is often a large difference between the cure cycle that parts are exposed to, because of variations in the loading of autoclaves and the number of different autoclaves that are used for the processing of a specific part. These cure cycle variations are another source of dimensional variability of the cured parts.

To study the effect of tooling material, tool-surface finish and cure cycle on the spring-in of composite C-channels, a set of experiments was performed. The specimens used were approximately 3 by 3 inches and were made of 16 plies $[0, +45, -45, 90]_{2S}$ of T800H/3900-2 unidirectional carbon/epoxy prepreg. The specimens were laid-up and cured on a solid aluminum tool (Figure 5A). Two C-channels were made at a time, and half of the tool was treated with release agent whereas the other half was only cleaned using acetone, in order to create different tool-surface conditions under each specimen. As an additional process variable, two different cure cycles were used: a single-hold cycle and a double-hold cycle (Figure 5B).



A) B)

Figure 5. A) Tool and parts, B) Cure cycles used in the study.

The experiment was designed based on process simulations using the COMPRO software. The premise is that for the single-hold cycle, the resin gels on the (only) hold at 177ºC whereas for the double-hold cure cycle, the resin gels on the first hold at 135ºC. The high thermal expansion of the aluminum tool will, during heat-up to the second hold at 177ºC, induce stresses in the part which results in extra flange spring-in, in addition to the "intrinsic" spring-in. Even if the composite part is stress free on a laminate level when the cool-down starts, there will be an "intrinsic" spring-in because of the difference in the thermal expansion in-plane and out-of-plane. The exact amount of the additional spring-in is dependent on the tool-surface condition, resulting in different amounts of mechanical interaction between the part and the tool. With no release agent, the part has a chance to bond to the tool after the resin gels. Bonding is not likely to occur with the use of release agent but there will still be some mechanical interaction between the tool and the part because of the way the C-channel encloses the tool. To test the hypothesis, two repeats of each test were performed.

In addition to the tests, finite element models of the processes were set-up in COMPRO to predict the outcomes of the experiments. Figure 6 shows the finite element mesh of the part and the tool used in the analysis. Note that only half of the part is modeled since the part and tool is symmetric with respect to a plane through the center of the web. The finite element mesh in Figure 6 represent a cross-section of the tool-part assembly shown in Figure 5. In the finite element mesh (Figure 6) the tool has a hollow center to simplify the mesh generation. This has a negligible effect on the results.

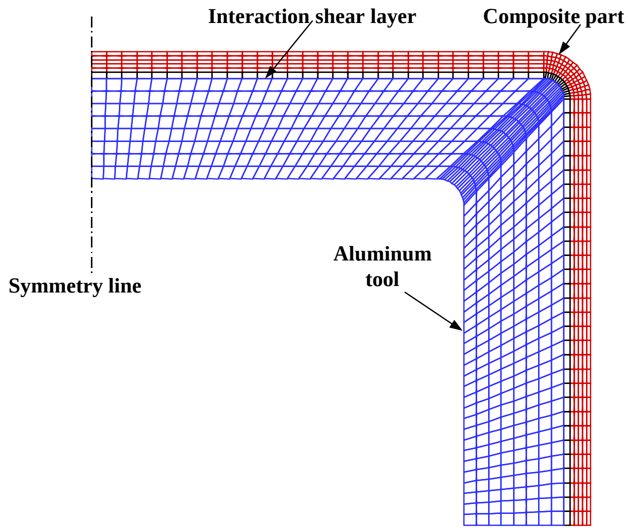


Figure 6. Finite element mesh of half of the C-channel shown in Figure 5A.

Figure 7 shows a comparison of the measured and predicted flange spring-in for the C-channel specimens cured using a single-hold cure cycle. The model predictions agree reasonably well with the experimental results, and for both the experimental and the model results there is approximately a 20% reduction in the spring-in for a part with no release agent compared to a part with release agent under it on the tool.

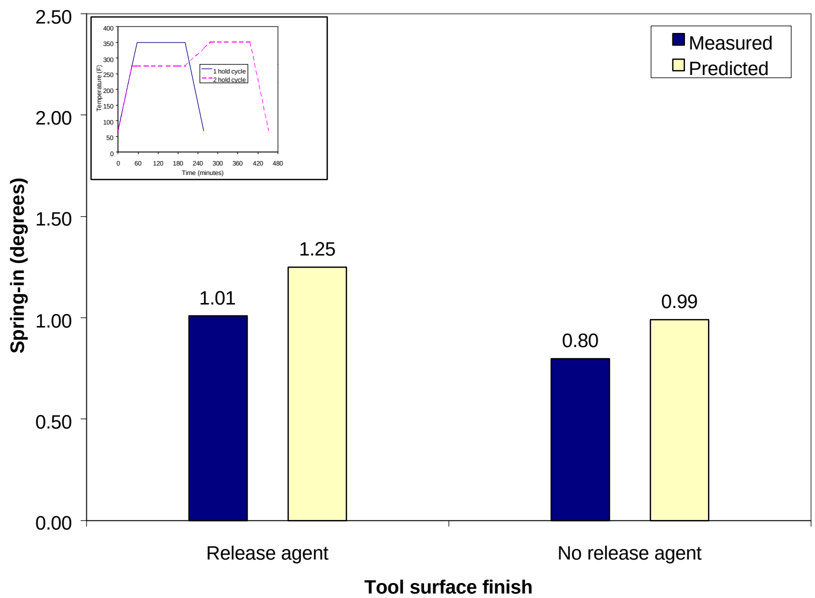


Figure 7. Measured and predicted spring-in for C-channels made on aluminum tooling cured with a single-hold cure cycle.

Figure 8 shows the measured and the predicted spring-in for the case of the double-hold cure cycle. Compared to the single-hold cycle, the spring-in is now significantly higher. The effect of the release agent is in this case more dramatic and with the opposite effect. The model predictions follow the experimental results but are 24% too high for the single-hold cycle and 20% too high for the double-hold cycle. It should be noted that the model is calibration free. The required thermo-mechanical material properties for the tool are taken from handbooks whereas the thermo-chemical and mechanical material properties for the T800H/3900-2 carbon epoxy prepreg are based on extensive coupon testing. Composite material properties in the model include: resin cure kinetics, resin cure shrinkage, resin viscosity and resin modulus development. A number of prepreg systems have been thoroughly tested and materials databases have been developed.

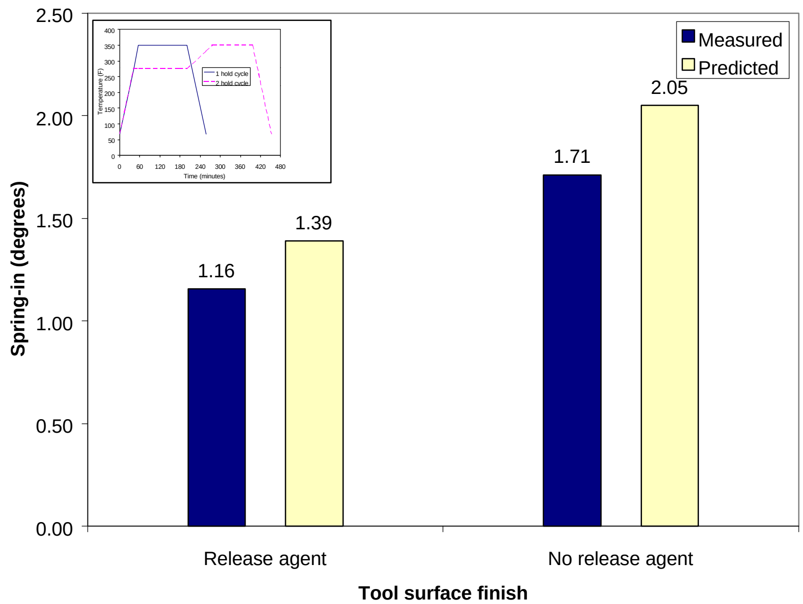


Figure 8. Measured and predicted spring-in for C-channels made on aluminum tooling cured with a double-hold cure cycle.

CONCLUSIONS

The study shows that there is a complex interaction between cure-cycle, tool surface condition and warpage (flange spring-in) of composite C-channels processed on an aluminum tool. The study shows that a two-hold cure cycle gives more spring-in than a single-hold cycle, irrespective of the tool-surface condition, because of "tool induced stretching" of the part during the second heat-up ramp. For a tool with release agent, the tool can stretch the part because of geometrical locking of the part on the tool. If no release agent is used on the tool and the part is allowed to "bond" to the tool, there will be a mechanical interaction between the tool and the part at the tool-part interface.

For a single-hold cure cycle, no release agent gives less spring-in than with release agent. The reason for this is not fully understood. For a two-hold cure cycle, no release agent gives a significantly greater spring-in than with release agent, which is in agreement with the concept of "tool induced stretching" and the effect of the mechanical interaction between the tool and part.

These somewhat surprising results of the current study illustrate the non-linear behaviour of most composite processes due to the exponential nature of the cure kinetics of most resin systems. It illuminates why there often is disagreement in industry about the effect of different tooling and process concepts – why some work in certain cases but not in others. Process modelling provides the research community with a tool to study and understand these phenomena in more detail.

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