P121

Decreasing Cure Cycle Time

Practice document

Document Type	Practice
Document Identifier	121
Themes	• Thermal management • Materials deposition and consolidation management • Residual stress and dimensional control management
Tags	• Development to production • Thermoset cure kinetics • Thermal transformation • Cure and crystallization
Objective functions	**Cost** Maintain **Rate** Increase **Quality** Maintain
MSTE workflow	Development
Prerequisites	• Effect of equipment in a thermal management system • Effect of material in a thermal management system • Effect of shape in a thermal management system • How to perform an experimental thermal profile • Thermal and cure/crystallization management (TM) • Thermal transformation • [[M105|]]

Q:"*I need to ensure that I have the fastest cure cycle possible as I need to maximize use of my cure vessel resources. How do I develop the fastest cure cycle possible for a given combination of cost and quality?*"

A:You can develop the fastest cure cycle possible by selecting the highest heating and cooling rates and cure temperature which allow you to meet the material's thermal specifications. For room temperature curing when the cure temperature is not actively controlled but a function of the ambient air temperature, the material's thermal specifications should take into account air temperature fluctuations to effectively constrain the duration of the material deposition step, and the thermal transformation or cure step before demoulding. The material's thermal specifications should also provide guidance on how to develop a post-curing step using active heating when the ambient temperature is too low to reach an appropriate final degree of cure or to meet the rate requirement by shortening the ambient cure.

Overview[edit | edit source]

Thermal transformation is one of the most critical manufacturing steps, which most manufacturing outcomes depend on. It allows the solidification of the resin by controlling or monitoring the resin's temperature. During a cure cycle, a thermoset resin undergoes significant transformation and evolves from a liquid viscous state, which allows forming and consolidation, to a final solid state before demoulding. As this happens, care must be taken to ensure that the level of cross-linking or cure is in the appropriate range: the resin must be neither under-cured nor over-cured. Given the exothermic nature of the cure reaction, it is possible to overheat a part, above the applied temperature, thus leading to heat damage. The part's consolidation and formation of residual stresses are also affected by the resin's solidification process. The development of a cure cycle therefore represents a major development step, which not only dictates thermal management outcomes but also impacts other manufacturing outcomes related to Materials deposition and consolidation management, and residual stress and dimensional control management.

Due to the high cost of capital equipment for thermal transformation, it is desirable to maximize the use of these types of equipment. There are several techniques for increasing throughput of the thermal transformation step (see other techniques in Troubleshooting a cure cycle for improved production rates) and developing the shortest cure cycle is the simplest one. Increases in productivity can be made by selecting the highest heating and cooling rates and cure temperature but this comes at the cost of increasing the risks of failing the material's thermal specifications and quality requirements as explained in more details below.

The development of a cure cycle is an iterative process during which an understanding of the thermal response of the part/tool assembly is developed. This understanding is necessary to define an appropriate cure cycle for the thermal transformation equipment in order to meet the material's thermal specifications. The material's thermal specifications are defined in the first place during the material development phase. The material's thermal specifications constrain the part's thermal history during processing and cure to ensure that the level of quality is in the appropriate range. Thermal specifications typically limit the lead and lag temperatures during a ramp as well as the maximum and minimum temperatures during a hold. If not available, they must be defined first.

Thermal management considerations[edit | edit source]

Link to thermal management

Fast heat up and cooling rates, as well as high cure temperature, can be selected according to the material's thermal specifications to allow for the shortest cure cycle. How fast the ramp rates or how high the cure temperature can be are ultimately defined by the material's thermal specifications as the cure cycle must allow the part's thermal history to meet the material's thermal specifications. For example, as explained in Systems Knowledge - effect of equipment in a thermal management system, increasing the heating rate has the combined effect of increasing the temperature gradients across the part and the thermal lag between the part and the curing environment, and may also lead to a larger exotherm. On the other hand, increasing the cure temperature has the effect of increasing the lead temperature and exotherm which might exceed the material's thermal specifications. If the cure cycle is not defined properly, the part's thermal history will fail the material's thermal specifications. It is recommended to start the iterative development process with low ramp rates and cure temperature and to gradually increase them and the complexity of the cure cycle.

To ensure thermal conformance as you are developing a cure cycle, you can evaluate the part’s thermal history by using:

1. Thermal Simulation
2. Thermal Test
3. Combination of thermal simulation and test

If you find that the part’s thermal history no longer meets the material's thermal specifications, you will have to continue the iterative development process and define and evaluate alternative cure cycles. For instance, if the exotherm is too large, you might consider lowering the cure temperature or the heating rate. Depending where you are in your development process, you might also decide to keep a problematic but shorter cure cycle and assess if by changing the tooling and/or equipment the given thermal specifications can be satisfied. For example, you might consider changing the thickness, substructure, or material of the tooling. As illustrated in Systems Knowledge - effect of tooling in a thermal management system, an exotherm can be mitigated by increasing the tool's facesheet thickness with the trade-off of increasing thermal lag. Replacing an aluminum tool with an invar one, for example, has such an effect.

Materials deposition and consolidation management considerations[edit | edit source]

Resin viscosity affects both flow dynamics during deposition and the subsequent consolidation step. A lower viscosity resin facilitates better flow and can lead to shorter cycle times. However, an excessively low viscosity may compromise the resin's structural integrity and final part quality. Higher viscosity resins may slow down the deposition and consolidation process, potentially elongating cure cycle times.

The fiber bed permeability dictates the ease with which resin can flow through the reinforcement. Higher permeability allows for better resin infiltration into the fiber bed and can reduce cure cycle time. However, very high permeability can cause defects, such as porosity.

For more information, see: Materials deposition and consolidation management (MDCM)

Residual stress and dimensional control management considerations[edit | edit source]

A faster cure cycle may limit the time available for proper material consolidation and adherence to desired shape. High heating and cooling rates can also cause high gradients of viscosity and degree of cure in the part and exasperate the development of residual streses and distortions due to non-uniform material properties. The rapid changes in temperature and viscosity gradients can result in uneven curing and cooling, leading to internal stresses that may impact the mechanical properties and shape of the final product.

For more information, see: Residual stress and dimensional control management (RSDM)

Related pages

Page type	Links
Introduction to Composites Articles	
Foundational Knowledge Articles	• Cure of thermosetting polymers - A162 • Degree of cure - A104 • Thermal phase transitions of polymers - A102 • Thermoplastic polymers - A161 • Thermoset polymers - A105
Foundational Knowledge Method Documents	• How to measure curing time and degree of cure - M100
Foundational Knowledge Worked Examples	
Systems Knowledge Articles	
Systems Knowledge Method Documents	
Systems Knowledge Worked Examples	
Systems Catalogue Articles	
Systems Catalogue Objects – Material	
Systems Catalogue Objects – Shape	
Systems Catalogue Objects – Tooling and consumables	
Systems Catalogue Objects – Equipment	
Practice Documents	• Decreasing Cure Cycle Time - P121 • Practice for developing a thermal transformation process step - P105 • Troubleshooting scale-up issues from thin to thick parts - P140 • Troubleshooting scaling-up issues from coupons to parts - P134
Case Studies	• Troubleshooting of room temperature processes for large recreational and industrial parts - C100

Perspectives Articles	• Composite materials engineering webinar session 3 - Constituent materials - Resin - A122 • Composite materials engineering webinar session 4 - Thermal management and resin cure - A123 • Composite materials engineering webinar session 5 - Manufacturing processes - Introduction - A124 • Composites Process Simulation: A Review of the State of the Art for Product Development - A283 • Dr. Anoush Poursartip's cdmHUB global composites expert webinar - A136 • Effect of cure on mechanical properties of a composite (Part 1 of 2) - A319 • Effect of cure on mechanical properties of a composite (Part 2 of 2) - A320 • Heat Transfer in Composites Processing - A321 • Introduction to the processing of thermoplastic composites - A322 • Resin Behaviour During Processing: What are the key resin properties to consider when developing a manufacturing process? - A257 • Understanding Polyester Resin Processing: The Effect of Ambient Temperature on the Final Part - A286

About **Help**

Degree of cure (DOC) is an indication of how far the chemical curing reaction (crosslinking process) has advanced in a thermoset resin.

DOC is defined with a number between 0 and 1 (or 0% and 100%) where 100% is a fully cured resin. It does not have to fully reach 100% for the resin to become solid or the part to be used. In some aerospace applications, resins are only cured to about 90%. Higher the degree of cure, higher the mechanical properties.

Outcomes represent the range of response/sensitivity to factory system attributes. Those that fail to satisfy manufacturing requirements are known as defects. Examples of manufacturing outcomes include process parameter outcomes, material structure outcomes, and material performance outcomes.

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.

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.

In composites processing, viscosity is an indicator of how easily the resin matrix will mix with the reinforcement and how well it will stay in place during processing. The lower the viscosity, the more easily resin flows. Resin viscosity ranges considerably across chemistries and formulations.

By scientific definition, viscosity is a measure of a material's resistance to deformation. For liquids, it is in response to imposed shear stresses.

Permeability refers to the resistance to fluid flow through a porous material.

- Resin flow through fibre
- Gas flow through prepreg