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P105

Practice for developing a thermal transformation process step

Practice document

Document Type	Practice
Document Identifier	105
Themes	• Thermal management • Material deposition management • Flow and consolidation management • Residual stress and dimensional control management
Tags	• Conductive heating • Convective heating • Cure and crystallization • Heat transfer • Process modelling • System optimization and robustness • Thermoset cure kinetics
Objective functions	**Cost** Maintain **Rate** Maintain **Quality** Maintain
MSTE workflow	Development
Prerequisites	• Integrated Product Development • Practice • Practice for Developing a Process Step • Thermal behaviour • Thermal and cure/crystallization management (TM)

Overview[edit | edit source]

This page provides guidance on taking the thermal transformation step from conceptualization to production. This includes conceptual screening and preliminary selection of tooling and equipment and then detailed finalization of the manufacturing (MSTE) system as a whole. The page is broken into three tabs which cover these activities. Conceptual screening covers initialization of tooling and equipment. For the equipment, this means to decide on its type and consequently on the heat transfer mechanisms involved. This decision should be based on thermal management considerations but should also take into account requirements from the other processing themes. Links to the Systems Catalogue provide a specific list of equipment and tooling to choose from. Preliminary selection involves maturing the material, shape, tooling and equipment and quantifying their parameters. This is done with consideration to foundational and systems level knowledge. Finally, detailed finalization covers the qualification process of ensuring that each component of the system functions as intended and part/material requirements are satisfied (i.e. outcomes are acceptable). Links to Systems Knowledge method documents are located here as well as in specify.

Introduction[edit | edit source]

The thermal transformation step allows to change the chemico-physical state of the resin by monitoring or controlling its temperature. During manufacturing, under the effect of temperature, the resin evolves from a liquid viscous state, allowing forming and consolidation, to a final solid state before demoulding. The thermal transformation cell allows to control the resin's liquid-to-solid transition and is concerned with meeting the specifications on the material system's thermal history.

In a typical manufacturing workflow, the thermal transformation step precedes the demoulding cell but depending on the process might also follow it when done in several steps. For instance, a room-temperature light-RTM production line might include a cure cell to control the degree of cure before demolding and a post-cure cell to control the final degree of cure. Depending on the manufacturing process, the thermal transformation step can also be integrated with the deposition, impregnation or compaction steps. For instance, in a room-temperature light-RTM process, the thermal transformation step happens concurrently with the impregnation and consolidation steps.

This Practice KPD provides the current practice to select, specify, and qualify a thermal transformation step for a given part and therefore combination of material and shape.

Significance[edit | edit source]

The thermal transformation step is one of the most critical manufacturing steps, on which depends most of the manufacturing outcomes. It allows to change the physical state of the resin by monitoring or controlling the resin's temperature. During manufacturing, the resin evolves from a liquid viscous state, allowing forming and consolidation, to a final solid state before demoulding. Thermoplastic resins are subject to the reverse transition first to reach the liquid viscous state. Thermoset resins undergo an additional transition, a rubbery-to-solid transition, before the final glassy solid transition.

The liquid-to-solid transition is the consequence of a thermally induced change of molecular structure, cross-linking for thermoset resins and crystallization for thermoplastic resins, which dictates the resin's process–structure–performance relationships. For instance, the operating temperature of a thermoset part depends on the resin's glass transition temperature which in turn is a function of its degree of cure (i.e. cross-linking density). The liquid-to-solid transition not only impact the thermal management (TM) outcomes (i.e. degree of cure, cure rate, etc.) but also the manufacturing outcomes related to material deposition management (MDM), flow and compaction management (FCM), and residual stress and dimensional control management (RSDM). For instance, the kinetics of the liquid-to-solid transition dictates, depending on the equipment and material system, the amount of resin flow and therefore MDM, FCM and RSDM outcomes such as fibre volume fraction, porosity content, and residual stresses. In order to control the liquid-to-solid transition, it is therefore key for the material system to follow a specified thermal history as defined by TM, MDM, FCM and RSDM requirements. The definition of the thermal specifications is part of the development process of the material system.

Prerequisites[edit | edit source]

- Materials science
- Processing science
- System interactions
- Thermal management

Practice[edit | edit source]

Screen
Select
Finalize

- Prior to beginning this stage, you should have already initialized your part's material and shape (see Practice for initializing part and materials page). For example, you might have screened a low temperature cure polyester resin and decided on a curved single skin design. The initialization of material and shape allows the initialization of the thermal transformation step and the conceptual screening of the type of tooling and equipment (i.e. autoclave, oven, hot press, heated tool, room-temperature process, etc.). Some questions to be answered at this stage include:
    - What sized part(s) do you want to make?
    - What types of materials do you want to process?
    - What range of capital costs do you want to invest?
    - What type of production rate do you want to achieve?
    - What type of production quality do you want to achieve?
- The information from the answers to the above questions will allow you to narrow down the thermal transformation step and screen the type of tooling and equipment.
- Refer to the Thermal transformation factory process step page for which equipment, tooling and consumables are relevant to your thermal transformation process step.
- When screening, the type of tooling and equipment and to address the quality requirements, you must consider whether or not the resulting manufacturing (MSTE) system will be able to meet the material's thermal specifications and so must take into account the:
    - Effect of material in a thermal management system and more specifically, the type of the matrix (i.e. thermoplastic or thermoset) and its thermo-chemical transitions (i.e., melting, crystallization and vitrification for thermoplastics, gelation and vitrification for thermosets) and related endo- or exothermic reactions,
    - Effect of the shape in a thermal management system and more specifically, the size and geometry of the part,
    - Effect of tooling in a thermal management system and more specifically, the material and geometry of the tool, and
    - Effect of equipment in a thermal management system and more specifically, the heat transfer mechanism offered by the equipment (i.e., conduction, convection or radiation).
- Ensure that the type of tooling and equipment screened can ultimately satisfy the defined cost, rate and quality (i.e. thermal specifications) outcomes.

- Select the screened tooling(s) and equipment by providing information on their parameters (see System parameters page of the Systems Knowledge volume), such as for the equipment:
    - Working volume

    - Critical dimensions (aspect ratio)
    - Working pressure and maximum temperature
    - Desired heating and cooling rate performances
    - Instrumentation requirements (thermocouples, pressure sensors, etc.)
    - Other factory requirements (vacuum lines, etc.)
- Perform thermal analysis of the screened manufacturing (MSTE) system(s) to specify and identify which one(s) allow to satisfy the material's thermal specifications. These analyses should focus on accurately determining the thermal management outcomes of the manufacturing system as a whole. Guides to carrying out these analyses can be found in the Systems knowledge method documents. In particular, the How to perform a numerical thermal profile method document is of most use here since the material, tooling and equipment may not be physically available at this stage. Alternatively, the thermal analysis can be done experimentally using a representative manufacturing system as explained in the How to perform an experimental thermal profile method document. A key outcome of this step is to turn the material's thermal history into an equipment temperature cycle. The next step described below ensures that the equipment can deliver the identified temperature cycle.
- Perform thermal analysis of the selected manufacturing (MSTE) system to convert the equipment heating and cooling rate performance specifications (i.e., maximum temperature, heating and cooling rates) into design requirements. The objective of this analysis is to right-size the heating and cooling systems, and in the case of a convection-based equipment, its airflow system. The way that the equipment responds to a thermal load, i.e. material, shape and tooling, is highly dependent on the thermal mass and thermal properties of the load and the heat transfer between the equipment and the load. Guides to carrying out this analysis can be found in the Systems knowledge method documents.
- Current practice hands over the responsibility of converting the performance specifications into design requirements to the equipment manufacturer. You might decide to rely on the equipment manufacturer expertise. In that case, you will have to define a representative thermal load for the equipment manufacturer. Be aware that current practice usually:
    - Consider the thermal mass of the representative load to size the heating and cooling systems.
    - Does not consider the real part's geometry and dimensions. This is of significance for convection-based equipment for which the heat transfer coefficient not only depends on the airflow system but also the part's shape.
    - Is done for an inert thermal load and does not take into account the material endo and/or exothermic behavior.

- Whereas the preliminary selection is generally done by analysis because the material, tooling and equipment have not been purchased yet, the detailed finalization and qualification is usually done experimentally. The procedure used to ensure that the thermal history of a composite part is compliant with the thermal specifications (i.e. ramp rate, maximum exotherm peaks, temperature uniformity, etc.) is called thermal profiling.
- Refer to the How to perform an experimental thermal profile method document for a step-by-step thermal profiling procedure.
- Note that the thermal profiling results can be used to improve the analyses done during the specification step and increase the understanding of how the system is performing.

Explore this area further

- Practice for developing a thermal transformation process step - P105
  - Developing production scale tooling - P129

Related pages

Page type	Links
Introduction to Composites Articles	
Foundational Knowledge Articles	• Conduction - A118 • Convection - A106 • Cure of thermosetting polymers - A162 • Degree of cure - A104 • Glass transition temperature (Tg) - A210 • Heat of reaction - A114 • Thermoplastic polymers - A161 • Thermoset polymers - A105 • Viscosity (resin) - A203
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	• Rheometer - A357
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

- Case Study: Optimizing a Press Moulding Process - A324
- 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
- Fabric Forming: how it affects design and processing, and how simulation can address this - A310
- Heat Transfer in Composites Processing - A321
- Interview with Prof. Kevin Potter - A134
- 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
- Simulation models for rapid liquid composite molding - A333.0
- Understanding Polyester Resin Processing: The Effect of Ambient Temperature on the Final Part - A286

About **Help**

A central processing theme in the manufacturing cycle. This theme is concerned with managing the thermal response of materials during storage and handling or parts/tools when they are subsequently heated.

Key components of all composite manufacturing processes. Collectively, the four themes represent the time-temperature-pressure-vacuum history, which is traditionally used to define a manufacturing cycle.

The four processing themes are:

- Thermal management
- Material deposition management
- Flow and consolidation management
- Residual stress and dimensional control management

(Same as "Theme")

In the context of knowledge in practice, knowledge refers to the systematic use of science based knowledge in composites manufacturing practice.

There is a distinction between experience based knowledge and science based knowledge:

- Experience based knowledge (‘know-how’) is an understanding of potential outcomes and their relationships that is founded on pragmatism and experience accumulated over time in individual programs, companies and in the industry more broadly.
- Science based knowledge (‘know-why’) is an understanding of potential outcomes and their relationships, based on the important processing physics, that is mature enough to be codified using the appropriate governing laws and constitutive equations.

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.

Resin transfer moulding (RTM) involves loading a preform into a two (or more) piece, matched tool, closing it, and injecting resin under pressure (~15-100 psi, or ~1-7 bar).

Well suited to small to medium sized parts, limited to large sizes due to injection pressure loads and tool cost.

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.

Any manufacturing and/or decision making activity that occurs during any stage of the development design cycle (e.g. conceptual design to production).

In the context of Knowledge in Practice, practice refers to the systematic use of science based knowledge to reduce composites manufacturing risk, cost, and development time.

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.

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.

A class of polymer, some common examples include polypropylene and polyethylene.

They soften and melt upon heating (i.e. potentially recyclable), high viscosity when melted, therefore difficult to saturate fibres. Usually needs a lot of pressure and heat to process.

The glass transition temperature (T_g) is the temperature region where the polymer transitions from a hard, glassy material to a soft, rubbery material. It is one of the most important properties of any amorphous polymer.

A central processing theme in the manufacturing cycle. It includes the steps primarily involved in moving material into the correct position on the tool or with combining fibre, resin and other constituents in-situ on tools.

A central processing theme in the manufacturing cycle. This theme relates to management of internal stresses that occur as the material undergoes differential thermal and physical phase change volume changes and viscoelastic property development.

Volume fraction of either matrix or fibres with respect to total composite volume (matrix + fibre).

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

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.

Experimental thermal profiling is a typical practice where part/tool temperatures and temperature rates are empirically measured using temperature measurement devices (typically thermocouples). This activity is performed to ensure that representative locations in the part of interest satisfy the cure window with respect to minimum/maximum heat up and cool down rates and length (duration) of temperature holds.