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A107

Thermal and cure/crystallization management (TM)

Systems knowledge article

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Introduction[edit | edit source]

Thermal management is concerned with knowing, understanding, and managing the thermal response of raw materials, tooling, and the part as they move through the factory. This theme covers the thermochemical management of materials in storage or handling and the subsequent thermal response of the tool and part assembly during cure. It is the first of the four themes to be considered as it begins from the moment the raw material is shipped and its outcomes are key to the other themes.

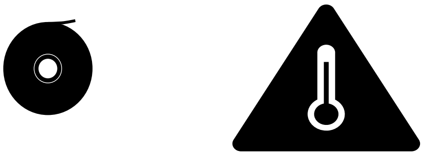
Significance[edit | edit source]

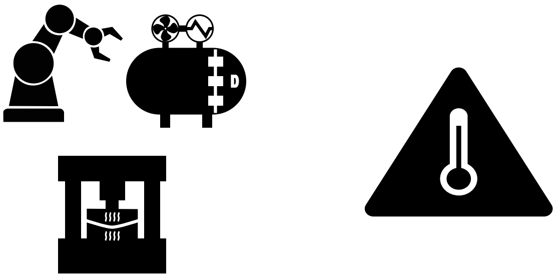
Link to system parameters - inputs and outcomes

Several manufacturing outcomes are directly related to thermal management. These include minimum and maximum part temperatures, cure or crystallization development, final degree of cure or final degree of crystallinity, final glass transition temperature, and others. In order to attain acceptable outcomes, it is crucial to manage the part's thermal response appropriately. Furthermore, if at any stage the thermal history of the part or raw material does not meet the intended material specifications, knock-on effects will be seen down the line across each of the subsequent themes[1]. This may negatively impact the final part quality. As such, thermal management is one of the most important considerations in any composite manufacturing system.

Scope[edit | edit source]

This page describes key processing steps from a thermal management and systems level perspective. The MSTEP approach allows one to break down the complex thermal management problem and to systematically analyzed the thermal interactions between the material (M), shape (S), tooling and consumables (T), and equipment (E) for a given step. Using this approach, the effect of each MSTE class on the thermal management outcomes is analyzed and illustrated in the following subpages:

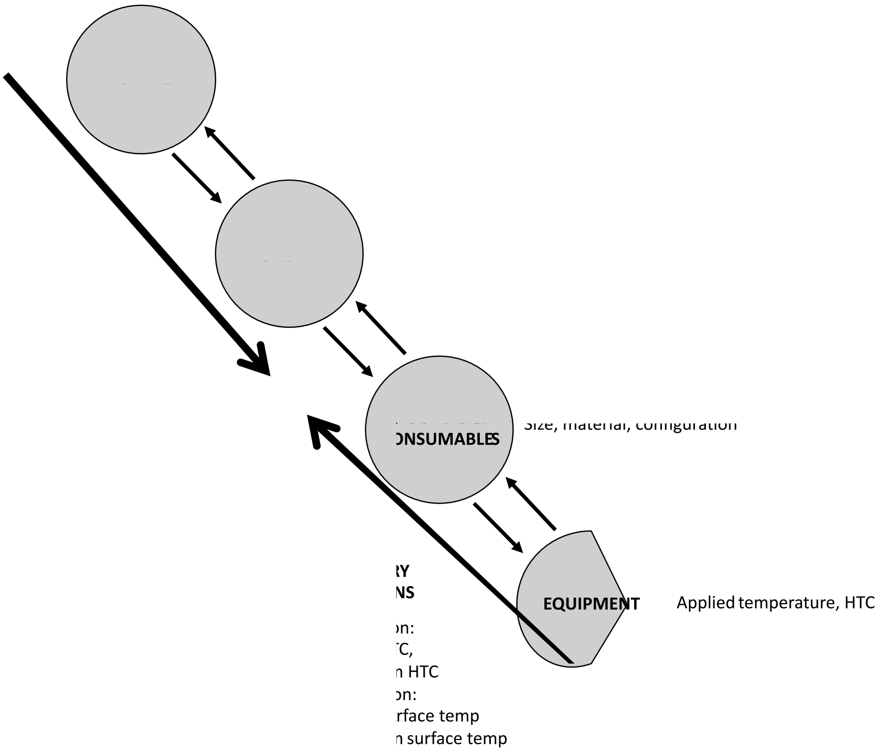




Effect of material in a thermal management system
Effect of shape in a thermal management system
Effect of tooling in a thermal management system
Effect of equipment in a thermal management system

Systems level approach[edit | edit source]

Overview[edit | edit source]



Interaction between manufacturing system classes in the context of thermal management. Adapted from[1].

A systems-level approach allows one to adequately describe the thermal management system and to identify the physics, the system MSTE components behaviors and parameters, and the initial conditions and boundary conditions governing the thermal management problem.

As the part moves through the factory, the thermal system in question may change depending on the process step (P). In any case, however, the process step can be described according to its MSTE parameters.

Take the thermal transformation step for example. In this scenario, the material (M) is a carbon/epoxy prepreg material, the shape (S) is a c-shape, the tooling (T) is an aluminum tool, and the equipment (E) is an oven. As the oven temperature ramps up during a cure cycle, the part temperature will increase as the heat from the oven is transferred to the surface of the part via convection on the bag side and through tool via conduction on the tool side. These two heat transfer mechanisms, conduction and convection, form the physics of the thermal management system. Conduction through the part-tool assembly (MST) depends on the material (M) and tool (T) thermal conductivities and specific heat capacities. Convection on the tool-side and bag-side defines the boundary conditions for the part-tool assembly. This is captured by the heat transfer coefficient (HTC). The HTC depends not only on the air flow within the oven (E) but also on the shape (S) of the part and the tooling (T) configuration. Thermal management is also a time varying problem where initial conditions are important. If the initial temperature of the system components is not as expected, the thermal response of the part will also be unexpected. Similarly, if the initial degree of cure of the material part is not as expected, the cure reaction will advance unexpectedly.

Key processing steps[edit | edit source]

Receiving[edit | edit source]

Link to receiving step within Systems Catalogue

It is important that the raw materials of the part are shipped under the appropriate conditions and do not exceed their shelf life. In particular, thermoset prepregs, some resins, and some adhesives require cold transport and storage in order to prevent premature advancement of cure. Upon receiving materials, it is best practice for part manufacturers (i.e. the receiving company) to have an incoming material acceptance plan with defined quality tests based on the material specifications. Depending on the industry or company, the material specifications may demand stringent quality tests or be as simple as visual or tactile inspection. In any case, knowing the temperature history of the materials during transportation allows engineers to make informed decisions on the state of the materials.

- Material (M) = Raw material (eg. prepreg, resin, core, etc.) and material specifications (eg. out-time, shelf life, storage conditions, etc).
- Shape (S) = Geometry of the material/part being shipped (eg. roll, flat sheet, etc.).
- Tooling and consumables (T) = Packaging, box, crate, etc.
- Equipment (E) = Transport vessel and vessel conditions (eg. truck, cooler, box, bag, active/passive cooling, presence of ice packs, etc.)

Storage[edit | edit source]

Link to storage step within Systems Catalogue

Similar to while in transportation, it is important that the raw materials of the part are stored under the appropriate conditions prior to use. For some thermosetting resins, this implies cold storage below -20°C. For core materials or consumables, typically room temperature storage is acceptable. Just as it is important to understand the temperature history of materials during transportation, it is equally as important to understand the temperature materials are subject to during storage. This includes the total out-time of the material, from shipping through to and including each time the material is taken in and out of the freezer. To truly understand the temperature history of a material, temperature fluctuations during storage should be tracked. In the case of cold storage, fluctuations may result from power outages, equipment malfunctions, or operator errors. In the case of room temperature storage, the changing of seasons, exposure to sunlight, and the opening and closing of doors may result in notable temperature fluctuations affecting the material properties. Aside from thermal considerations, humidity and UV exposure are other factors that should also be monitored.

- Material and process (M) = Raw material (eg. prepreg, resin, core, etc.) and material specifications (eg. out-time, shelf life, storage conditions, etc).
- Shape (S) = Geometry of the stored material/part (eg. roll, flat sheet, etc.).
- Tooling and consumables (T) = Packaging, box, crate, etc.
- Equipment (E) = Storage container/unit (eg. freezer, shelving, etc.)

Deposition[edit | edit source]

Link to deposition step within Systems Catalogue

It is during the deposition stage that the part begins to take form. Therefore, it is crucial that defects are not introduced to the part at this stage. From a thermal perspective, this generally means not exceeding the working time of the material. That is, completing deposition of the material within the allotted time as defined by the material specifications. Working time varies depending on the chemistry of the material and the manufacturing process. For example, the working time involved in a prepreg layup compared with resin infusion is vastly different. As with the previous process steps, good temperature control is ideal to achieve optimum part quality. This includes temperature control of the involved equipment and the tool(s) upon which the material is being deposited.

- Material (M) = Materials used in deposition and the associated specifications (eg. working time, vacuum cycle, etc.).
- Shape (S) = Geometry of the part achieved during deposition (eg. curved, flat, thick, thin, etc.)
- Tooling and consumables (T) = Tool that the part is deposited on (eg. layup tool) and the consumables used in the deposition/bagging of the part (eg. release agent/film, breather, vacuum bag, etc.)
- Equipment (E) = Equipment used to deposit/manipulate the material/consumables on the tool (eg. AFP, ATL, etc.), or the environment in which material deposition occurs (eg. layup room, layup table, etc.)

Thermal transformation[edit | edit source]

Link to thermal transformation step within Systems Catalogue

This is the most important manufacturing step from a thermal management perspective. It is during this stage that the part achieves its final in-service properties. As such, it is significantly impacted by the temperature history during the thermal transformation stage. Typically, for every thermosetting resin or prepreg system there is an associated manufacturer recommended cure cycle (MRCC) defined. For large or complex parts, specific cure cycles may need to be developed in order to achieve the desired mechanical properties. Together, the purpose of the thermal system during thermal transformation is to cure/crystallize the composite part to achieve the required mechanical properties. There are three primary aspects to a thermal transformation system. Namely, the cure environment, cure cycle, and the thermal history of the part, wherein the latter is an outcome.

- Material (M) = Part material system(s) and the associated specifications for cure (eg. cure cycle, maximum temperature, etc.).
- Shape (S) = Geometry of the part during thermal transformation (eg. curved, flat, thick, thin, etc).
- Tooling and consumables (T) = Tool that part is cured on/in and consumables from bagging (eg. breather, vacuum bag, etc.).
- Equipment (E) = Thermal transformation equipment (eg. oven, hot press, autoclave, etc)

The curing equipment includes all adjoining, but chemically inert, materials such as the equipment, tooling, and consumables. Together, these components determine the boundary conditions of the system and the mode of heat transfer. In a thermally activated system, the part-tooling assembly is coupled to a heat source such as an oven, autoclave, or other non-convective heating source such as electric cartridge heating. Taken together, this coupled system defines the cure environment and has a great effect on the outcome of the curing process. In a production environment, many of the cure environment parameters may not be easily changed. Therefore, it is important for process engineers to understand the constraints of their specific cure environment to mitigate the risk associated with a non-flexible system. The following are examples of five common cure environments.

- Autoclave - High pressure, high temperature, forced convection with high HTC
- Oven - Vacuum pressure, high temperature, forced convection with moderate HTC
- Room temperature cure - Vacuum pressure, room temperature, natural convection with low HTC
- Hot press - Very high pressure, high temperature, conduction
- Heating blanket - Vacuum pressure, moderate temperature, conduction

The visible outcome of the thermal transformation step is a cured composite part. However, in the context of thermal management, the key outcome is the thermal history of the part as a function of both location and time during processing. This can be verified by running a formal thermal profiling study which measures the temperature of the part during the curing process at a large number of discrete points. To ensure a good part, all measured temperatures must conform to the specification processing window. In production, the part thermal history can be checked by measuring the temperature of the part, or the tool, in strategic locations identified through the thermal profiling study.

The thermal history of the part is a defined by the cure cycle, cure environment, part material properties, dimensions of the part, and the location of the part within the cure environment. As such, it is a complicated problem that must be approached systematically in order to understand and achieve the desired outcome.

Cooking Analogy[edit | edit source]

Thermal management is not a theme unique to composites manufacturing and many analogies can be drawn. One of particular relevance is cooking chicken in an oven. This scenario is analogous to the thermal transformation stage of composites processing. The MSTE system description of cooking a chicken in an oven is as follows.

- M = Chicken and cooking requirements for chicken (e.g. internal temperature must reach 165 \(\pm\) 5°F)
- S = Breast of uneven thickness (thick on one end, thin on the other)
- T = Pan or pot the chicken is in
- E = Oven

Internal temperature of chicken depends on the geometry of the chicken breast and the pan the chicken is placed on (frying pan if cooked on the stove).

Temperature of chicken depends on the airflow and location (if cooked in an oven).

Here, the cure environment with respect to the chicken breast is the oven and the pan (or pot). The cure cycle is the set temperature of the oven and the temperature ramp rate, although the latter may not be controllable in a conventional oven. The thermal history of the chicken breast is defined by the oven temperature, the thermal mass of the pan, its location in the oven, and the geometry of the chicken breast. The intended thermal history outcome is that the chicken breast reaches an even temperature across it's thickness in order to be fully cooked. If the internal temperature is never above 160°F it will be undercooked and if it is greater than 170°F it will be dry or burnt. Therefore, the problem is constrained. An acceptable outcome is that the chicken must reach an internal temperature of 165 \(\pm\) 5°F.

Just as is common for composite parts, however, the chicken breast is not uniform in thickness across its length. Moreover, there are likely hot and cold spots within the oven. This makes cooking the chicken more difficult. Without proper thought, a basic cooking cycle will likely result in the thin sections cooking first and becoming dry and/or the thick sections remaining undercooked. In order to mitigate this, the MSTE parameters must be controlled. The part (chicken breast) is likely fixed, unless the user wishes to chop the chicken into smaller pieces to improve heat transfer. The material system (chicken) is fixed, unless a different meat is to be chosen in its stead, and the cooking requirements are also fixed. That leaves E and T to be changed. Potential solutions are provided below.

Improvements to E: For a more accurate temperature control, it is better to slowly cook the chicken in a convection oven. Airflow increases the rate of heat transfer and creates a more uniform temperature distribution across the oven. Similarly slower heating rates ensure more uniform cooking. Of course, not all ovens are convection ovens and the heating rate may not be tailorable. Therefore, the user must decide if these is are necessary features and if it's worth changing the equipment entirely to either a more advanced oven or to an entirely different heating system - a slow cooker for example.

Improvements to T: Rather than cooking the chicken on a pan, the user could opt to cook the chicken in a dutch oven. Due to its larger thermal mass, and because the chicken will be placed in a smaller volume (i.e. isolated from the rest of the oven), the temperature distribution will be more even.

In the above analogy, the comparison was drawn only between the cooking stage and cure/crystallization. Of course, prior to cooking, there are a series of thermal management steps which again are analogous to composites manufacturing. First, one must go to the grocery store and buy the chicken. In doing so, there must be some transport vessel available (shopping cart, bag, etc.). Before buying, the consumer should check the expiry date and do a quick sensory inspection to ensure the chicken is not bad. This is analogous to the receiving stage for composites. Next, the consumer stores the chicken in either the fridge or freezer to be used later. It is important, that the chicken not wait at room temperature (or even fridge temperature) for too long, or the chicken will start going bad. This is representative of the shelf life of a composite and is analogous to the storage stage. Finally, prior to cooking, the chef must prepare the meal. This may involve placing the chicken on a pan or casserole dish (deposition onto a tool), and then marinating or adding additional ingredients (layup). Finally, the chef may opt to put aluminum foil (consumable) over the meal prior to placing it in the oven. While chefs typically aren't worried about the "working time" of their chicken while preparing their meal, it is still a factor. If one takes hours to prepare the meal, there is the chance the chicken will start going bad. This last step is analogous to the layup/bagging stage for a composite.

In the case of composites manufacturing there are additional considerations that are not captured in the above analogy. The main difference is that for thermosetting materials there is a heat generation term due to polymerization which must also be managed. Additionally, while implementing slow heating rates and long cooking times may be acceptable in cooking food, these aren't ideal for manufacturing composite materials as they can add considerable cost to the process.

Maturity[edit | edit source]

Explore this area further

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Systems Catalogue Objects – Equipment
Practice Documents
Case Studies
Perspectives Articles

References

1. ↑ [1.0] [1.1] [Ref] Fabris, Janna Noemi (2018). *A Framework for Formalizing Science Based Composites Manufacturing Practice* (Thesis). The University of British Columbia, Vancouver. doi:10.14288/1.0372787.

About **Help**

A key component 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 "Processing themes")

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.

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.

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.

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.

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.

Pre-impregnated (prepreg) material refers to fibre that is already combined with resin. It is the most common material form used in aerospace.

During prepreg production, (e.g. fibres are run through a resin bath), prepreg is heated and partially cured to B Stage (< 5 % degree of cure). Thermoset prepregs (e.g. epoxy prepreg) have to be kept in a freezer at around -20 °C. At room temperature, the epoxy starts to cure.

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.

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.

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.

Manufacturer's Recommended Cure Cycle (MRCC).

With regards to manufacturing, risk is the combination of the probability and consequences of undesirable manufacturing outcomes. Manufacturing risk can lead to technical issues, program/schedule delays, and cost overruns.

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.