A4

Systems Knowledge
Systems knowledge article

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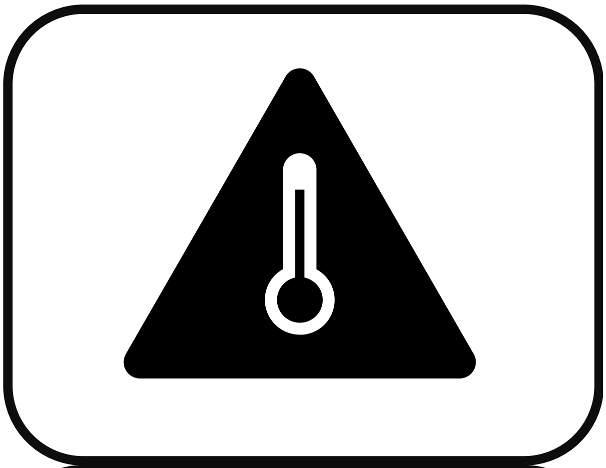
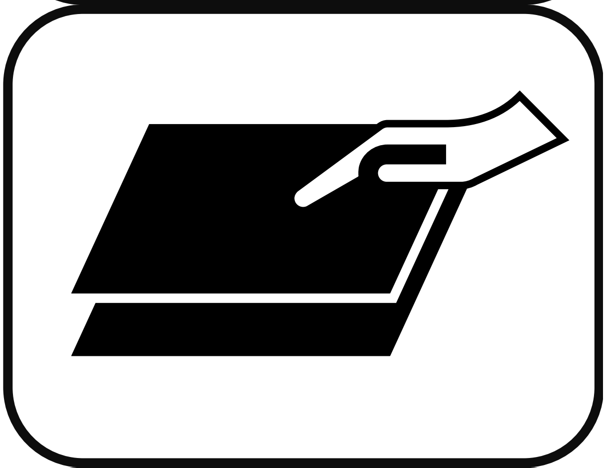
Welcome to the Systems Knowledge volume. This volume lays out and describes a science-based, systems level approach to tackle composite manufacturing problems. Just as in engineering design[1], all manufacturing processes can be broken down into components and sub-assemblies, which form the basis of a manufacturing system. In that way, a systems-level approach can be applied to manufacturing engineering. System's knowledge focuses, from a physics-based perspective, on the interaction between system components and how these interactions influence the system outputs. The framework for this method of thinking, as applied to composites manufacturing, was developed as part of the doctoral work of Dr. Janna Fabris[2] under the supervision of Dr. Anoush Poursartip.

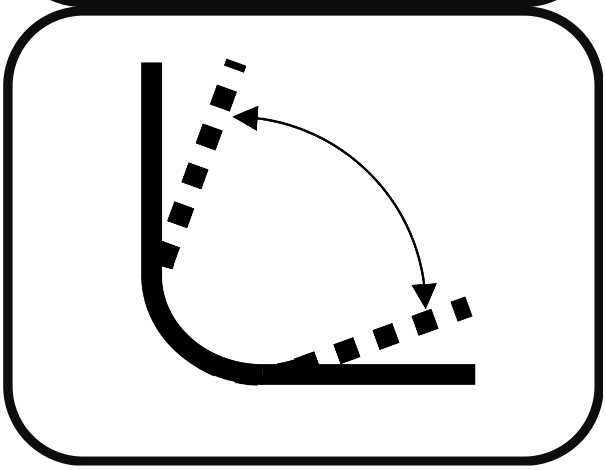
The design and workflow of a manufacturing factory is a complicated problem, but one that is important for ensuring part quality. Approaching the factory from a systems level perspective allows for the problem to be deconvoluted. A factory can be broken into multiple cells where the different process steps of the factory take place, from receiving of raw materials through to shipping of the completed part. Raw material is brought into the cells, shaped on tooling, and passed through various equipment to create the part. The interaction between the material (M), shape (S), tooling and consumables (T), and equipment (E) for a given process (P) define the part quality. This is the basis of the MSTEP approach used throughout the KPC. The interactions between M, S, T, and E (known collectively as MSTE) can be categorized into themes such as thermal and cure/crystallization management (TM), deposition and consolidation management (DCM), residual stress and dimensional control management (RSDM), machining and assembly management (MAM), and quality control management (QCM).

This volume focuses on the interactions between material, shape, tooling, and equipment with respect to the part for each of the manufacturing themes. Refer to the Level I view to navigate to the Systems Knowledge content quickly. Refer to the Level II view to navigate the Systems Knowledge content with some direct links to important, detailed concepts. Refer to the Level III view to gain a more in-depth understanding of the systems-approach to composite manufacturing.

Level I
Level II
Level III





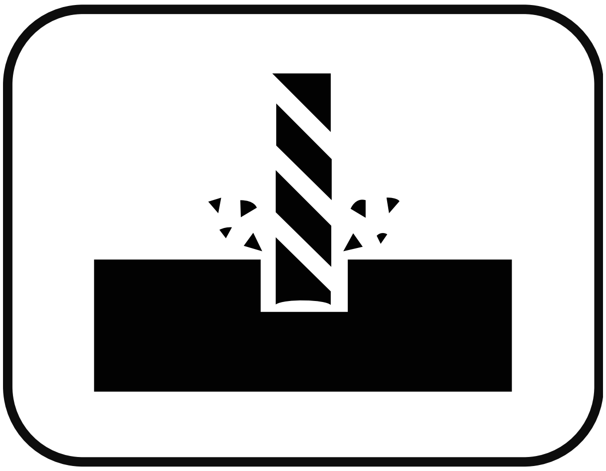


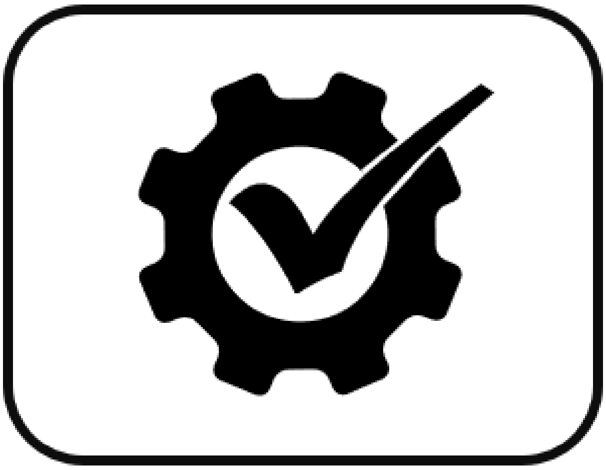
Thermal and cure/crystallization management
Materials deposition and consolidation management
Residual stress and dimensional control management

Thermal management is concerned with managing the thermochemical response of materials in storage/handling as well as the thermal response of parts during deposition and thermal transformation. A large focus is placed on the lattermost activity as this is the crux of thermal management. Click here to explore thermal and cure/crystallization management.

Materials deposition and consolidation management deals with the steps involved in placing material into the correct position on a tool or with combining fibre, resin, and other constituent materials on tools. Examples include robotic-placed prepreg tape on a tool and resin infusion of a fabric preform draped on a tool. It also includes managing physical response of parts/tools when the resin is predominantly in a liquid phase (eg. pre-gelation, pre-solidification) and the prevention of manufacturing defects such as wrinkling and porosity. Click here to explore deposition and consolidation management.

Residual stress and dimensional control relates to the management of internal stresses that occur as the material undergoes differential thermal and phase change volume changes, and the matrix gains elastic memory due to viscoelastic property development. This includes controlling the changes in the mechanical response of parts and subsequent geometric changes when removed from tools or when parts are post cured. Click here to explore residual stress and dimensional control management.





Machining and assembly management
Quality/inspection management

Machining and assembly management deals with aspects related to finishing of composite parts and assembly/joining of composite parts. Finishing operations include part trimming, hole drilling, hole cutting & general machining. Assembly operations include fastener assembly methods, inserts, bonding, co-curing, etc. Assembly can also include shimming of components, which is a direct consequence of residual stress and dimensional control management. The priority in this theme is how to machine and assemble your composite parts without sacrificing quality. Click here to explore machining and assembly management.

Quality/inspection management is concerned with monitoring the quality of the manufacturing processes at every step of the part production. This might include explicit inspection steps using specific inspection equipment, or it may be more subtle in using process data that is already collected as part of the manufacturing process in order to verify that the process is operating within specifications. Click here to explore quality/inspection management.

Read more

How to use this volume[edit | edit source]

Volume framework[edit | edit source]

This volume lays out and describes a science-based, systems level approach to tackle composite manufacturing problems. This approach is at the core of the KPC framework and is utilized and expanded upon in proceeding volumes. When navigating this volume, users will be reintroduced to the notion of composite manufacturing as a systems problem. As users navigate to more advanced pages, Foundational Knowledge content and physics-based simulations are used to demonstrate and explain how system components influence composite manufacturing outcomes. The effect of individual components on the system are described in detail in these pages.

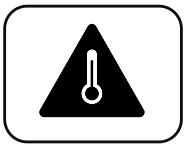
This volume focuses on the material, shape, tooling, and equipment interactions for various themes. It does not go into detail into how these interactions may influence different processes. In this regard, the volume isolates, and discusses in detail, the MSTE component of the MSTEP approach. To gain a complete understanding of the MSTEP approach refer to the systems approach to composite materials page. To learn more about the individual factory objects, process steps, and factory layout, visit the Systems Catalogue volume.

Volume features[edit | edit source]

Coming soon.

Content[edit | edit source]

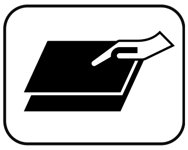
Thermal and cure/crystallization management[edit | edit source]



Thermal and cure/crystallization management is concerned with managing the thermochemical response of materials in storage/handling as well as the thermal response of parts during deposition and thermal transformation. A large focus is placed on the lattermost activity as this is the crux of thermal management.

Learn more about thermal and cure/crystallization management:
- Effect of material
- Effect of shape
- Effect of tooling
- Effect of equipment

Materials deposition and consolidation management[edit | edit source]



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Learn more about material deposition and consolidation management:
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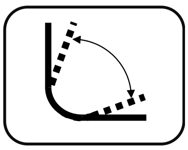
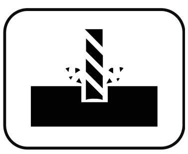
Residual stress and dimensional control management[edit | edit source]



Residual stress and dimensional control relates to the management of internal stresses that occur as the material undergoes thermophysical-induced volume changes and viscoelastic property development occurs. This includes controlling the changes in the mechanical response of parts and subsequent geometric changes when removed from tools or when parts are post cured.

Learn more about residual stress and dimensional control management:
- Effect of material
- Effect of shape
- Effect of tooling
- Effect of equipment

Machining and assembly management[edit | edit source]



Machining and assembly management deals with aspects related to finishing of composite parts and assembly/joining of composite parts. Finishing operations include part trimming, hole drilling, hole cutting & general machining. Assembly operations include fastener assembly methods, inserts, bonding, co-curing, etc. Assembly can also include shimming of components, which is a direct consequence of residual stress and dimensional control management. The priority in this theme is how to machine and assemble your composite parts without sacrificing quality.

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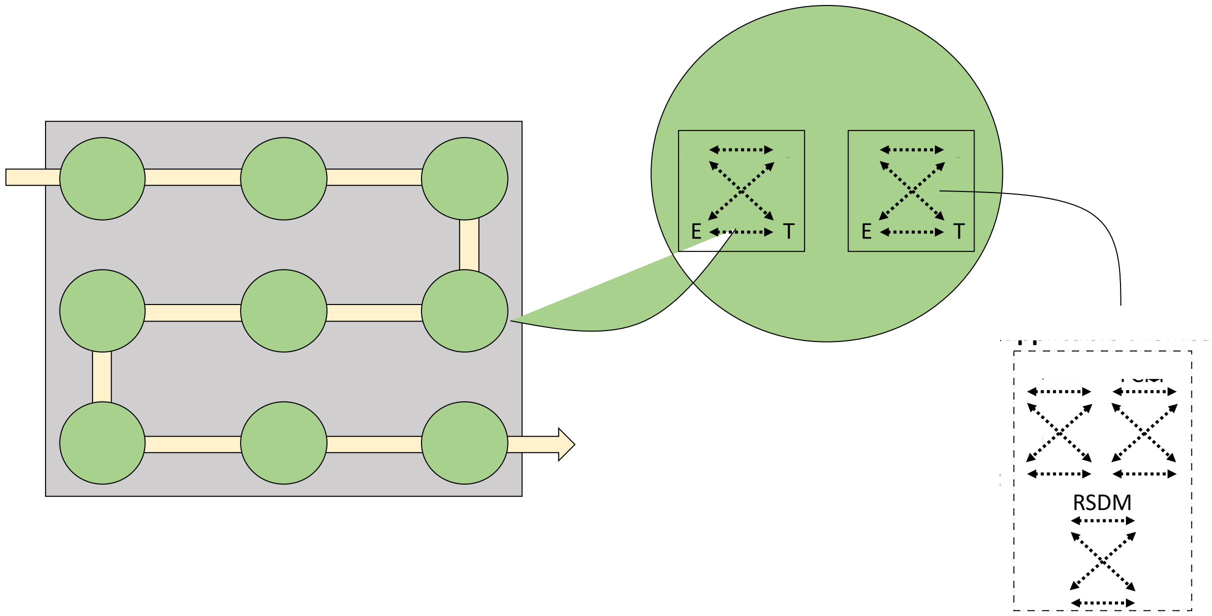
Volume features[edit | edit source]

Coming soon.

System description[edit | edit source]

A factory is set of cells, each occupying a physical space, where one or more processing steps occur. In a composites manufacturing factory, there can be many different cells arranged in various ways depending on the part being produced. However, there are typically 14 general process steps that occur. They are as follows.



Systematic breakdown of a composites manufacturing factory

Generalized composite processing steps:

1. Receiving
2. Testing
3. Storage
4. Preparation
5. Deposition
6. Forming
7. Thermal transformation
8. Demoulding
9. Trimming and machining
10. Inspection
11. Assembly
12. Coating
13. Reporting
14. Packaging and shipping

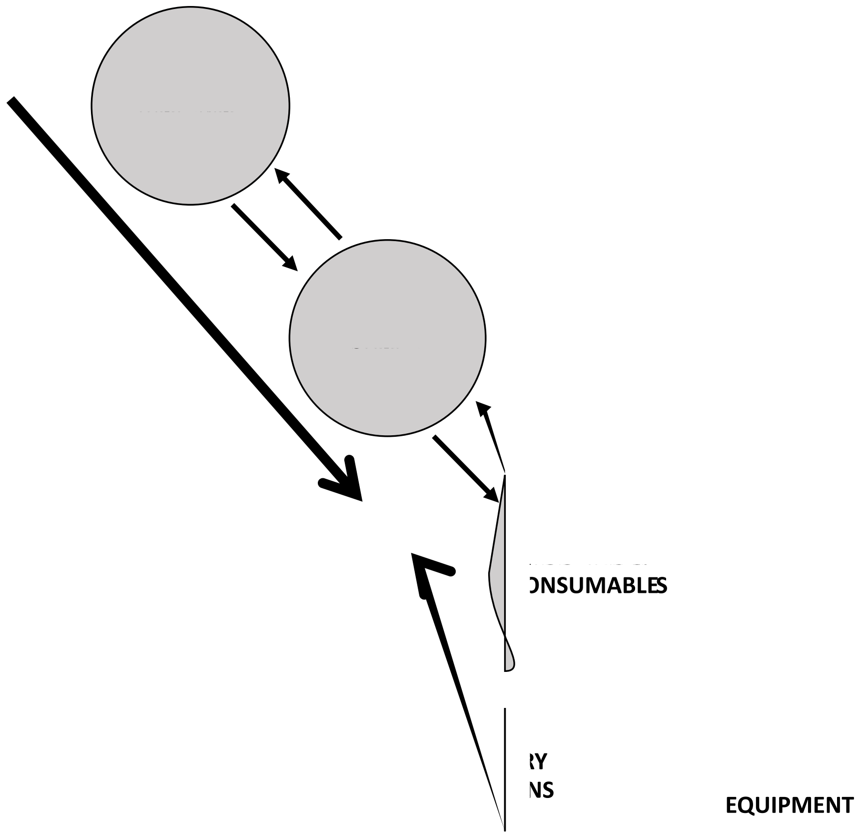
Although most composite processing steps can be categorized according to the above list, the order in which these process steps occur is not fixed. Moreover, each generalized process step may comprise numerous specific steps depending on the material state and part being manufactured.

Each factory cell represents a sub-system within the entire factory. These sub-systems comprise the individual process steps occurring, which can be described and analyzed by the interactions between the materials (M), part shape (S), tooling & consumables (T) and equipment (E) within[2]. It is the equipment and tooling that act on the material to produce the part with a defined shape. The nature of these interactions can be categorized into different themes. That is, the set of governing equations, constitutive models, and material science that define the process interactions. With regards to processing of composite materials, there are four primary themes. They are thermal management (TM), material deposition management (MD), flow and consolidation management (FCM), and residual stress and dimensional control management (RDM). A given manufacturing process may incorporate multiple themes, however a discretized structure such as this may be used to systematically approach the problem.

In any system, there are parameters that one may wish to track in order to evaluate the system. These are known as outcomes and are representative of the outputs of the system. Evaluation of these outcomes are what define producibility. If the outcomes are acceptable, then the intended part quality at that stage of the manufacturing process has been achieved. In order for the finished part to achieve its intended quality, all outcomes from each factory cell must be acceptable. If the intended outcomes of an early cell are not achieved, knock-on effects may appear later on. Hence, why part/material quality should be checked at each stage of the manufacturing process. An example is the part temperature. An intended outcome of the system may be to have the part remain within a given temperature range over an alloted period of time during cure. If the condition is met, it's acceptable and therefore part producibility is satisfied; if not, it's unacceptable. Within each cell, the M, S, T, and E (MSTE) parameters are what define the state of that system. These parameters interact with one another to determine the system outcomes. Since outcomes are what define producibility, this becomes the crux of a systems-level problem - i.e. how does one tailor the system parameters for the applicable themes to achieve the desired outcomes?

Classes[edit | edit source]

Link to the Systems Catalogue page on factory objects



Interaction between MSTE classes

For each process step (P) there is always equipment (E) involved which acts on the part in someway. The part itself has a shape (S) and is comprised of a material system (M). Furthermore, the part is typically supported on tooling (T). Take hot press forming of a carbon-epoxy ski for example. The equipment is the hot press, the tooling is the mould that provides shape to the ski, the material is the specific carbon-epoxy blend (including its processing specifications), and the shape is the geometry of the ski with all of its intricacies.

The breakdown of a process step into the relevant material, shape, tooling, and equipment for a given processing theme is the backbone of the systems approach to composites manufacturing, as it allows for the problem to be setup and defined. Once the system is defined from the MSTE parameters, the physics-based interactions leading to the outcomes can be understood for each process step.

Material (M)[edit | edit source]

Link to material page within Systems Catalogue

The material represents the part material system and its processing specifications. For example, epoxy vs polyester resin and their processing requirements are material parameters. The interaction between the material and shape controls the outcome sensitivity of the system with respect to the part. For example, the material system and the part geometry define how the part will respond to an imposed temperature.

Shape (S)[edit | edit source]

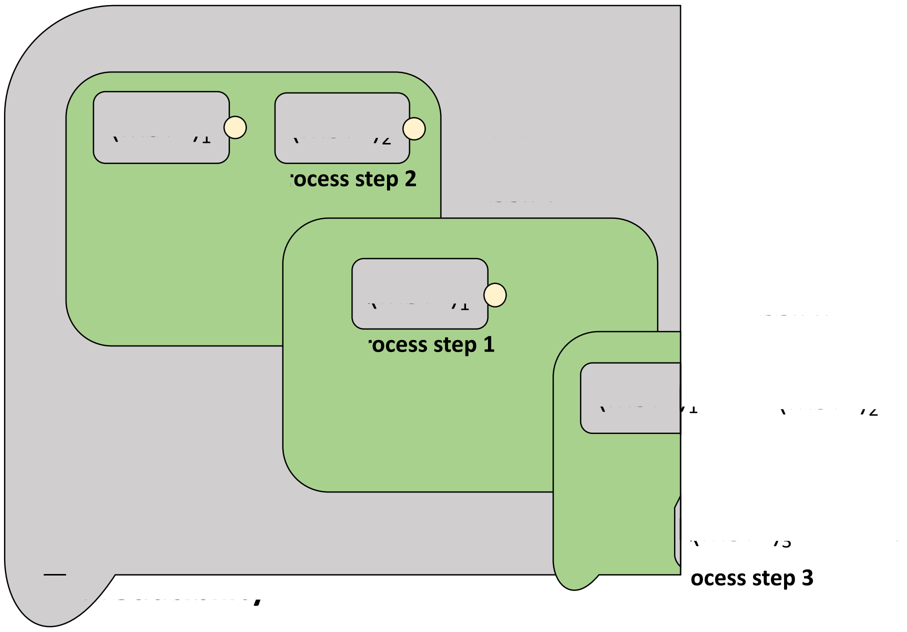
Link to shape page within Systems Catalogue

The shape represents the geometry of the part. This includes thickness, surface area, volume, contours, and any geometrical features within the part (ply drops for example). Together, the shape and the material define the part.

Tooling and consumables (T)[edit | edit source]

Link to tooling and consumables page within Systems Catalogue

Tooling interfaces directly with the part, providing shape and imparting a boundary. Tooling may move between factory cells or be an asset of a single cell. For example, a part may be placed on a tool in the deposition cell and then transported to the thermal transformation cell where it is cured. Consumables are one-time-use objects that serve any number of purposes. A vacuum bag is an example of a consumable. The part is always bound by some form of tooling or consumable. Therefore, external stimuli (such as temperature) must move from the equipment, through the tooling, and into the part.



Representation of the MSTE classes within the factory

Equipment (E)[edit | edit source]

Link to equipment page within Systems Catalogue

Equipment are physical assets within a factory cell that provide external stimuli to the system. Their purpose is dependent on the stage of processing they are intended for. For example, a hot press is a piece of equipment that may be used to cure a composite, thermoform, or do both. In that regard, a hot press is a piece of equipment that may be used during thermal transformation and/or deposition. Together, the equipment and tooling represent the system boundary conditions with respect to the part.

Process step (P)[edit | edit source]

Link to factory process flow within Systems Catalogue

The process steps are the individual processes that occur throughout the factory. Each can be described by its MSTE components and their interactions. Each process step exists within one or more factory cells (physical spaces within the factory).

Factory (F)[edit | edit source]

Link to factory page within Systems Catalogue

The factory is the aggregation of all MSTE objects, all processing steps, and the factory cells. In other words, it is the collection of all items, actions, and physical spaces involved in manufacturing. An important stage in the factory flow is evaluating the outcomes after each process step in order to demonstrate producibility. Producibility refers to the acceptability of parts as they move through the factory, based on part quality. Quality is determined by the outcomes of the MSTE interactions for each process step (i.e. each MSTEP occurence).

Themes[edit | edit source]

The process steps that occur within each cell of a composites factory can generally be grouped under one of the four following themes.

Thermal and cure/crystallization management (TM)[edit | edit source]

Link to thermal management page

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Materials deposition and consolidation management (MDCM)[edit | edit source]

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Residual stress and dimensional control management (RSDM)[edit | edit source]

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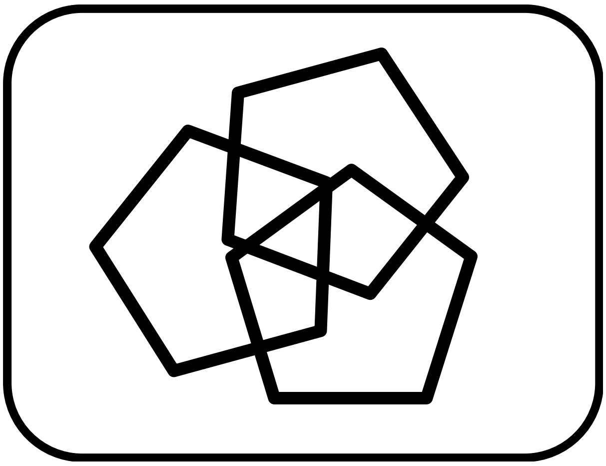
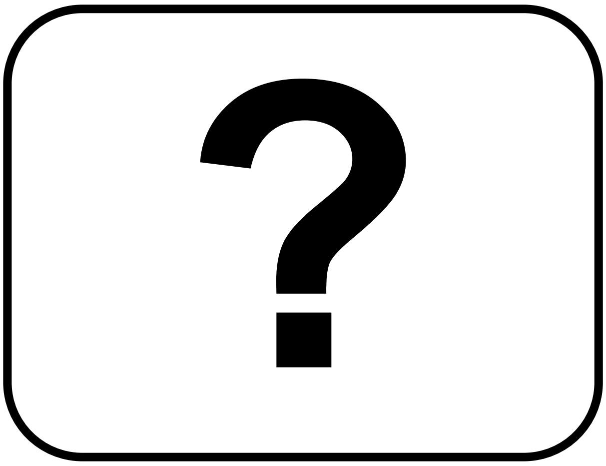
References

1. ↑ [Ref] Ashby, M.F. (2011). *Materials Selection in Mechanical Design*. Elsevier. doi:10.1016/C2009-0-25539-5. ISBN 9781856176637.
2. ↑ [2.0] [2.1] [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

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.

Separating a complex process involving several interacting phenomenon into several simple processes involving straightforward (easy to understand) phenomena.

Material and process (M), Shape (S), Tooling and consumables (T) & Equipment (E) - all have an interlinked effect on the Process step (P). (See MSTE factory ontology)

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.

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.

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.

The individual materials that combine to form the composite material. The constituent materials are separate and distinct on a macroscopic level.

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.

‘Preform’ is the term for the fibre reinforcement. This is the stage between the raw material form after it is processed into an architecture (fabric, mat, etc.) and becoming a composite.

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

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.

An individual station within a factory where a given set of tasks are accomplished (also known as a "work cell"). Some cells may directly add value to the product (e.g. deposition), while others may serve support roles that are critical to maintaining part quality (e.g. receiving, storage, inspection & shipping).

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 concerned with managing changes in the physical response of parts/tools when the resin is predominantly in a liquid phase (e.g. pre-gelation, pre-solidification) and the prevention of manufacturing defects.

The capability of the manufacturing process to produce parts of acceptable quality (e.g. meet engineering, manufacturing, regulatory requirements), repeatably and robustly.