Introduction to Quality Assurance and Control in Composites Manufacturing

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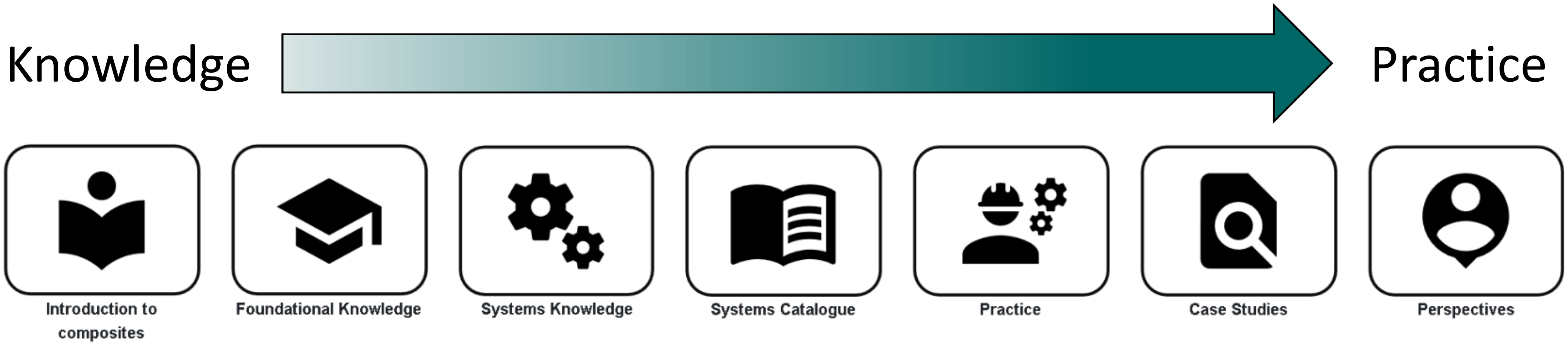
KNOWLEDGE IN PRACTICE CENTRE (KPC)

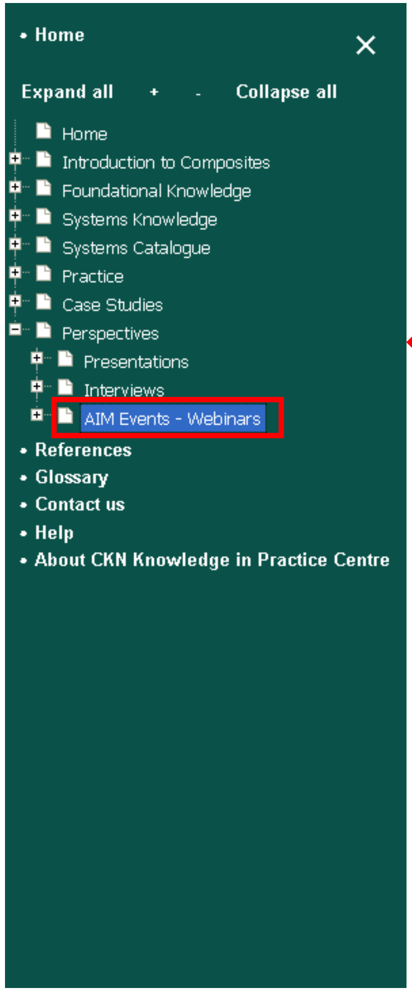
- A freely available online resource for composite materials engineering:

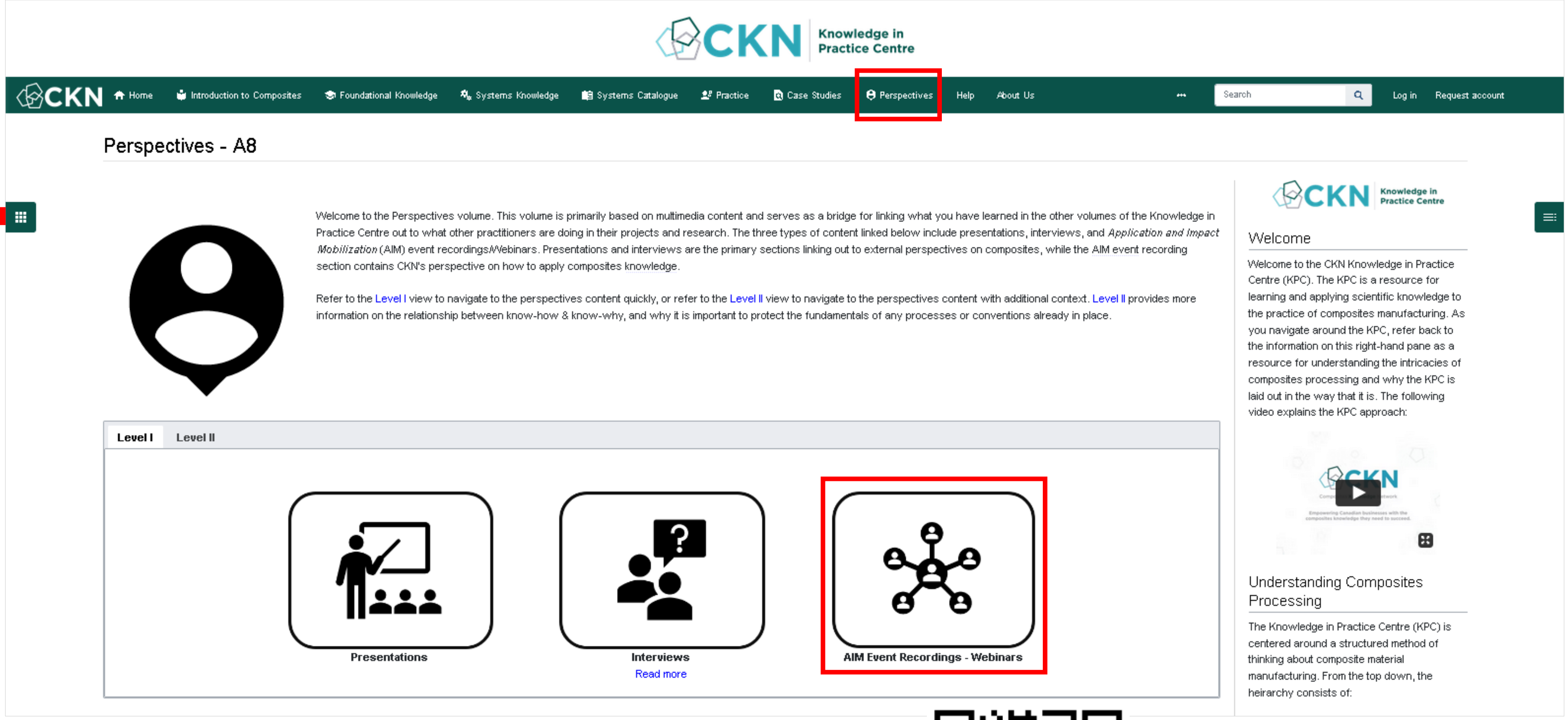
  compositeskn.org/KPC

- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



PAST WEBINAR RECORDINGS AVAILABLE





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Today's Topic:

Introduction to Quality Assurance and Control in Composites Manufacturing

OUTLINE

- Introduction
  - What is quality
  - Quality assurance vs control
  - History of quality
  - Quality control in composites vs metals
  - Quality control in composites
- Stages of Quality Assurance and Control
  - Material acceptance
  - Process specification
  - Personnel
  - Testing
- Example and Conclusion

INTRODUCTION TO QUALITY

- Quality is "flawlessness"[1]
  - Flawlessness is not possible, how do we assess and manage it?

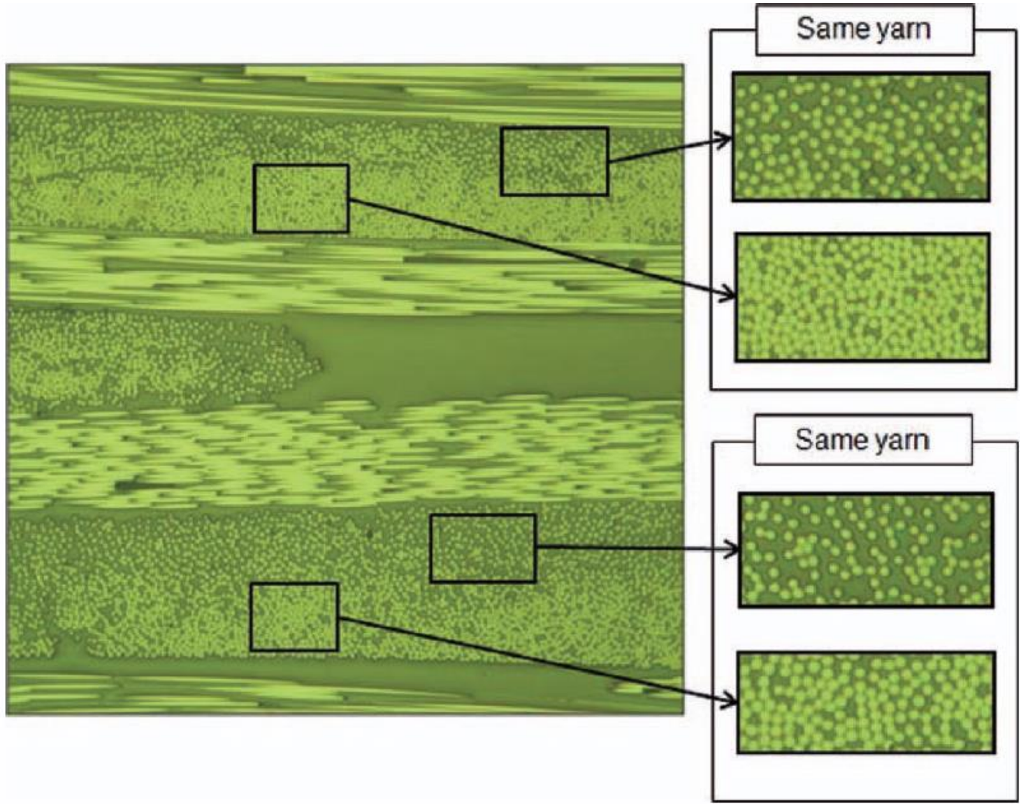
- Factors affecting quality of composite parts:
  1. Raw material quality
  2. Manufacturing process
  3. Inspection process

- Considerations for developing a system to produce parts of quality:
  1. Designing parts with QA/QC in mind
  2. Tracking quality throughout the process - traceability
  3. Documenting and working on continuous improvement
  4. Using feedback and customer satisfaction and iterating through process designs

[1] Henson, G.A. (2001). Introduction to Quality Assurance.

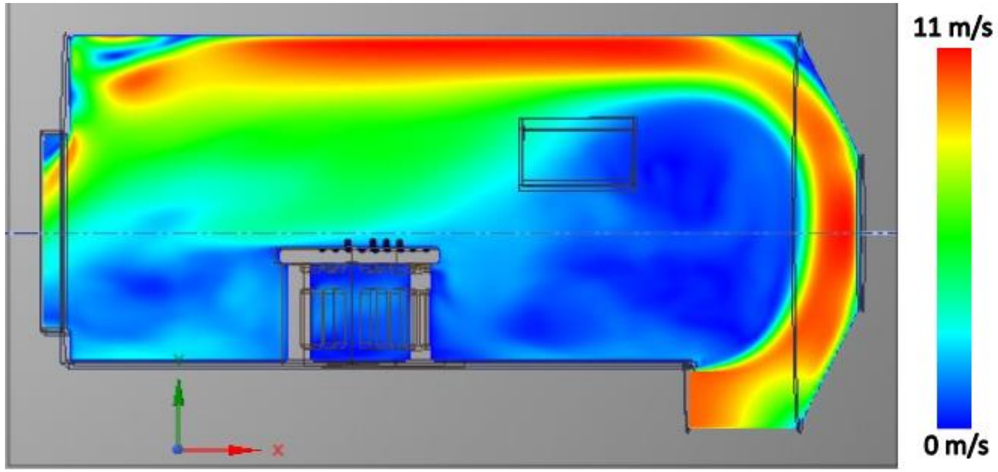
VARIABILITY IN COMPOSITE PROPERTIES

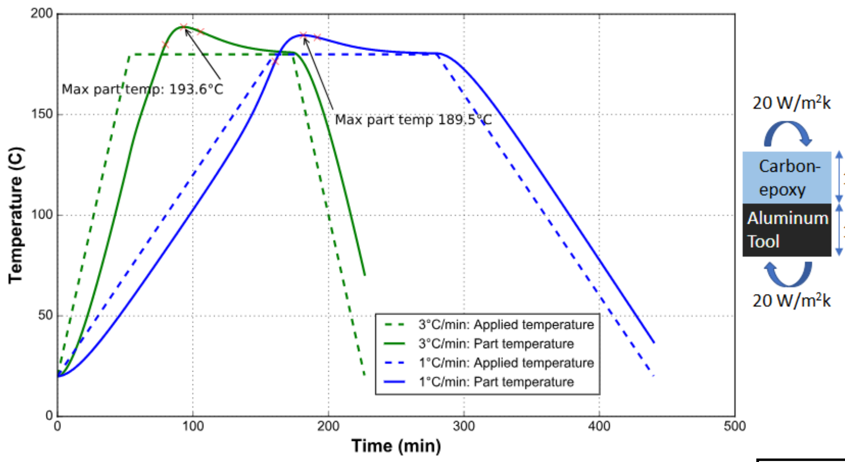
Material



Uneven local fibre volume fraction inside yarn in 12K, variations of fibre volume fraction between 20% and 75% [1]

Processing





[1] Figures adapted from Olave, M., Vanaerschot, A., Lomov, S. V., & Vandepitte, D. (2012). Internal geometry variability of two woven composites and related variability of the stiffness. *Polymer composites*, 33(8), 1335-1350.

HISTORY OF QUALITY CONTROL

Late 13th century	Early 19th century	Late 19th century	Early 20th century	WWII	1946	Mid 20th century	Late 20th century	21st century
Craftsmanship and Guilds	Industrial Revolution Factory System	The Taylor System	Quality Processes and SQC	Sampling and Standards	ASQ (then ASQC) formed	Company-wide Quality Control in Japan	Total Quality Management in the U.S.	Quality 4.0

[1]

Craftsperson had a tremendous personal stake in meeting costumers' needs for quality

Taylor's approach improved productivity but had a negative effect on quality

Processes were included in quality practices, processes can be analyzed using statistical techniques

In a factory system, quality was ensured through the skill of laborers supplemented by audits and inspections

During WWII, sampling inspection is used to replace unit-by-unit inspection

Total quality management and ISO 9000 series were established to embrace quality through the entire organization

[1] from American Society for Quality Control, http://asq.org

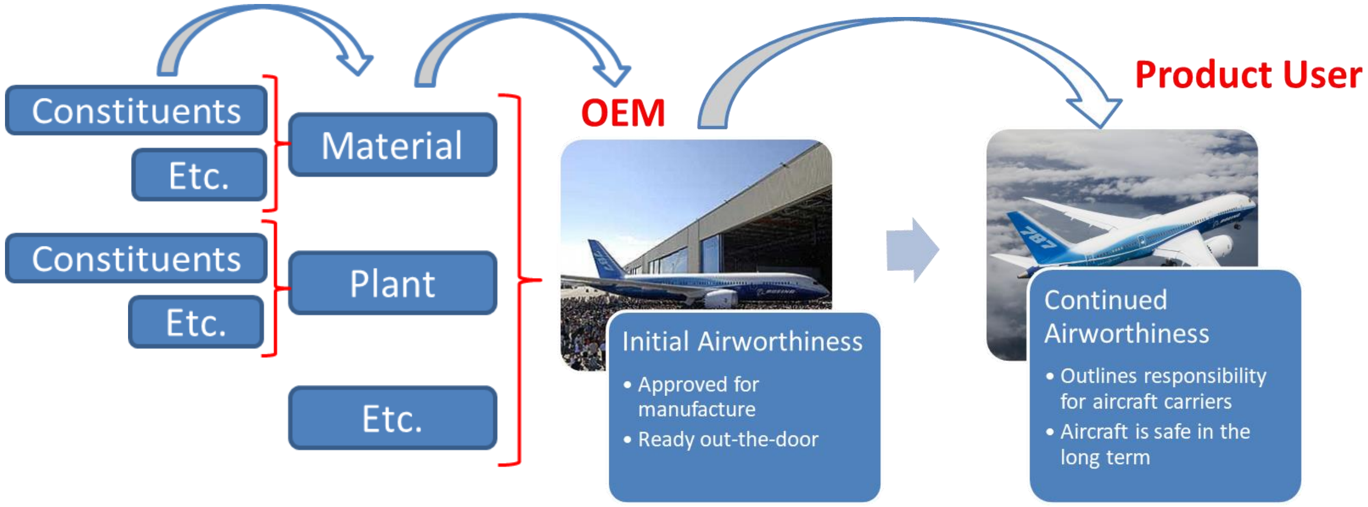
QUALITY ASSURANCE VS QUALITY CONTROL

Quality Assurance [1]

- Proactive process that focuses on preventing defects by establishing policies and refining manufacturing procedures
- For composites, it involves tracking, reviewing and confirming:
  - i. Conformity of raw materials
  - ii. Engineering requirements (process specs, acceptance criteria etc.)
  - iii. Tooling condition
  - iv. Planning documents
  - v. Operator and inspector training
  - vi. In-process control of critical parameters (out-time, cure parameters etc.)
  - vii. Statistical process control (SPC) data
  - viii. Non-destructive evaluation

Quality Control [1]

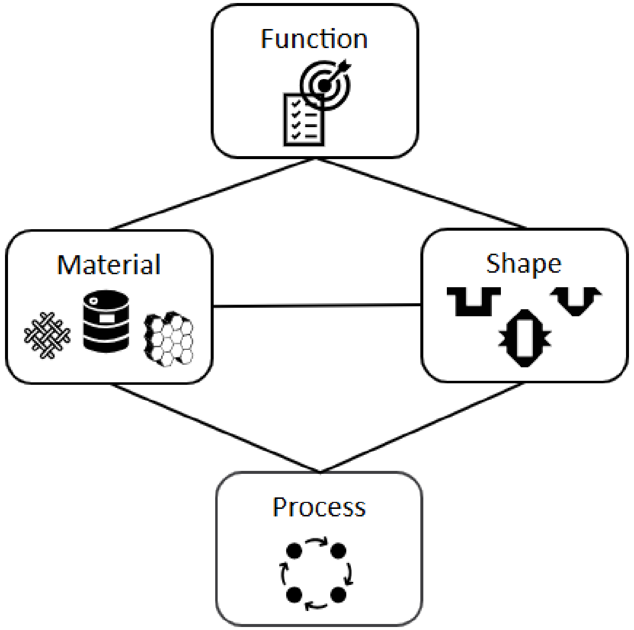
- A reactive process that focuses on identifying and fixing defects
- In the context of composites manufacturing:
  - Ensure consistently manufactured products meet specification
  - Satisfy transition of responsibility down the supply chain



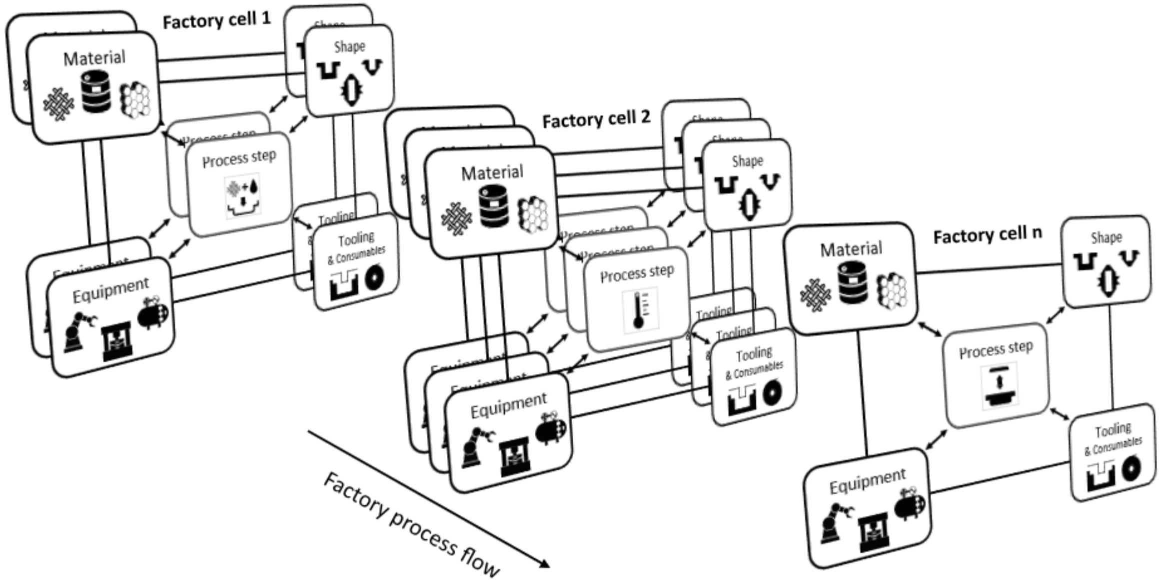
Miracle, D. B., Donaldson, S. L., Henry, S. D., et al. (2001). ASM handbook (Vol. 21, pp. 107-119). Materials Park, OH: ASM international.

QA/QC IN COMPOSITES VS METALS

- Metals Vs Composites
  - *"Unlike parts which use metallic materials in the manufacturing process, the material properties of a composite structure are* ***manufactured into the structure****..."* FAA AC 21-26, Page 2
  - *"Quality control procedures, which often make use of the lower levels of building block tests, ensure the* ***material used to fabricate production aircraft parts remains invariant****."* Modified from FAA AC 23-20, Page 9.



Traditional (Ashby) framework for engineering design and manufacturing



CKN's expanded MSTEP approach to manufacturing

QUALITY CONTROL IN COMPOSITES

QC and QA practices are tailored to each stage of the supply chain:

- Constituents > prepreg manufacturer (**material acceptance**)
- Prepreg manufacturer > OEM (material acceptance, **process specification**)
- OEM manufacture (process specification, **DT/NDI**)
- OEM > Product user (**NDI**)

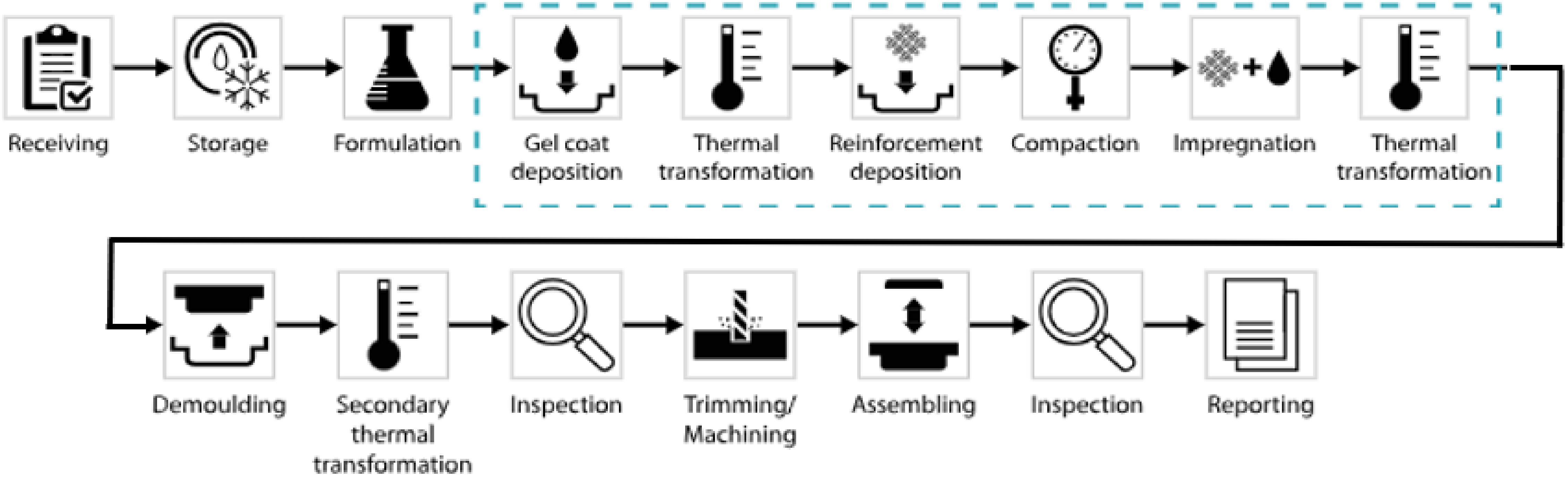
Many parts of QA and QC for composites are linked and shared, as it tries to adapt the same framework historically used in metallic fabrication. [1]

Composite components QC stages [2]

QC Stage	Details
• Material quality approval	• Receipt checks • Storage
• Manufacturing quality control	• Personnel • Documentation • Process control
• Process verification	
• Manufactured component inspection	

[1] Miracle, D. B., Donaldson, S. L., Henry, S. D. et al. . (2001). ASM handbook (Vol. 21, pp. 107-119). Materials Park, OH: ASM international.
[2] Teagle, P.R. (1983). The quality control and non-destructive evaluation of composite aerospace components. *Composites, 14*(2), 115-128.

EXAMPLE – QC/QA IN VARTM PROCESS



DOCUMENTATION

Documentation

- A range of QC documentation is used by manufacturers, including:[1]
  - **Component drawings**: a controlling document giving component geometry, including layup details, may call up other relevant QC documentations
  - **Process specifications**: general requirements of the process
  - **Technique sheets**: requirements relating to particular materials or components, usually contains QC procedures and acceptance limits
  - **Planning sheets**: travels with the components, gives details of all operations to be carried out, stamped by an approved inspector when operation is complete
  - **Component history cards**: travels with the component and records all relevant process details and QC test results, stamped by an approved inspector

[1] Teagle, P.R. (1983). The quality control and non-destructive evaluation of composite aerospace components. *Composites, 14*(2), 115-128.

DOCUMENTATION

Documentation

- Material specification documents include: [1]
  - High-level information (resin content, cured ply thickness, fiber, areal weight, fiber type)
  - Test methods used on the product to meet material requirements
  - Statistical methods used (raw data collected from tests, procedures used)

- Process control documents include methods and details to control: [1]
  - Raw materials used (chemistry, properties, supplier information)
  - Mixing/combining processes
  - Equipment used (calibration certificates)
  - Test methods used on the product to meet material requirements
  - Statistical process controls used (variables, ranges, limits, SPC analysis procedures)

[1] Henson, G.A. (2001). Introduction to Quality Assurance.

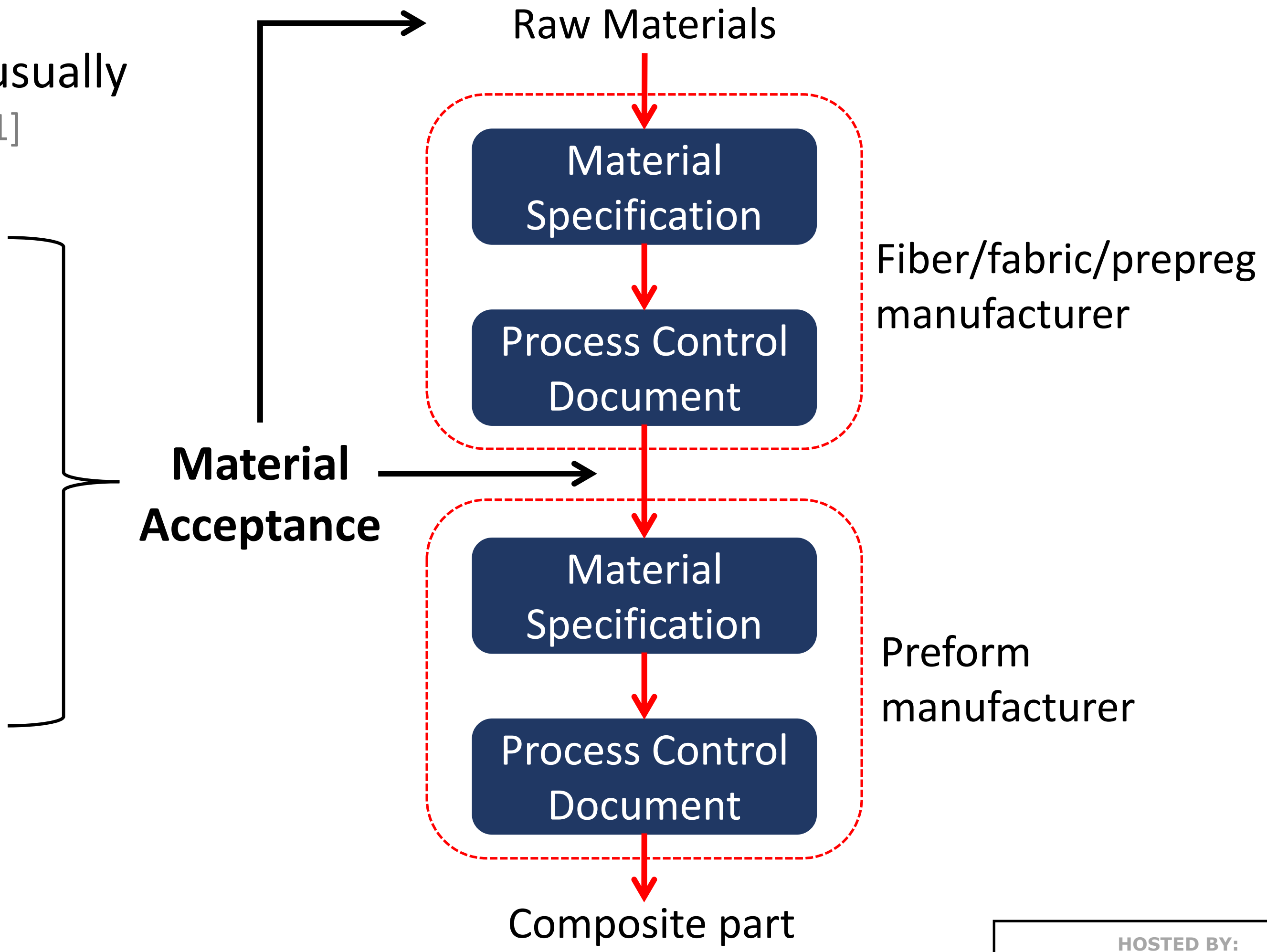
MATERIAL ACCEPTANCE

- "Material specifications define the material's attributes and the qualification tests." FAA AC 23-20, Pages 8, 24.
- **FAA AC 23-20** describes this in the context of the AGATE program
  - *To develop a database of material properties;*
  - *To continue surveillance of material and process;*
  - *To show that minor changes to material and processes do not affect base material properties;*
  - *To make final adjustment on material and process specifications for specific application and demonstrate that it has minor effect on base material properties.*
- **FAA Technical Report [DOT/FAA/AR-02/110]** describes more details on how to develop a material specification

MATERIAL ACCEPTANCE

Visual examination and other simple tests are usually carried out on a sampling basis to determine: [1]

- Freedom from untagged cosmetic defects such as splits, gaps, whorls and edge straightness
- Fibre distribution
- Surface tack
- Resin/fibre content
- Volatile content
- Flow characteristics



[1] Teagle, P.R. (1983). The quality control and non-destructive evaluation of composite aerospace components. *Composites, 14*(2), 115-128.

MATERIAL ACCEPTANCE – TRANSPORT AND STORAGE

- Potential for contaminants to be introduced to raw materials
- Rolls of fibre fabric material:
  - Typically labeled with material type and weight, logged for reference
  - RFID or QR code system for identification and tracking can be used
  - Fibre rolls should be kept horizontal or fibers can become misaligned
- Prepreg: [1]
  - The material is hermetically packed in a plastic bag and in a fully labeled carton including: material name and type, material quantity in length, expiration date, batch number, etc
  - Temperature logged so time can be subtracted from the out-time
  - Sensitive to moisture when thawing

Carbon fiber prepreg label [1]

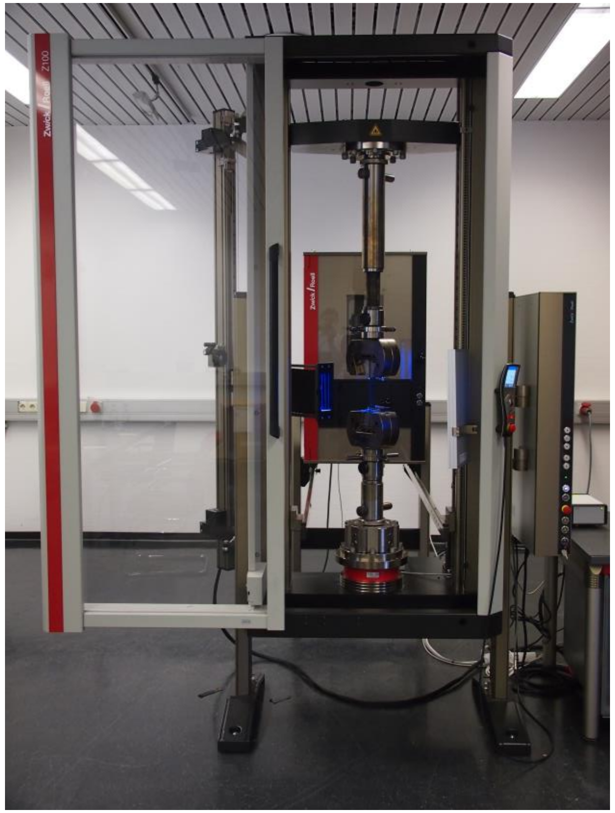
Single-use temperature logger

[1] Szymański, Z. (2017). Quality control process of manufactured composite structures. Prace Instytutu Lotnictwa, (1 (246), 95-103.

MATERIAL ACCEPTANCE – TRANSPORT AND STORAGE

- Dry fibre:
  - Some fibre is sensitive to UV
  - Sensitive to impact and should be handled carefully
  - Sizing on the fiber can break down over time and can be sensitive to temperature and humidity, fibers should be stored at a stable temperature and dry humidity
- Uncured resin:
  - Containers should be labeled with receipt date, manufacture date, expiry date
  - Containers can be arranged in a FIFO (first in first out) manner
  - Crystallization can occur
  - Important to keep container sealed as moisture and contaminants can effect the resin

MATERIAL ACCEPTANCE – MECHANICAL PROPERTIES



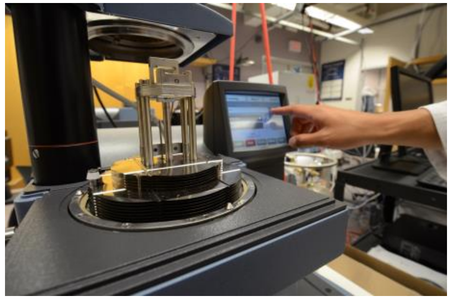
Typical tests for unidirectional tape [1]

- **ASTM D7264** – Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials
- **ASTM D2344** – Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials
- Thickness measurement and volume fraction measurements (consolidation behavior)

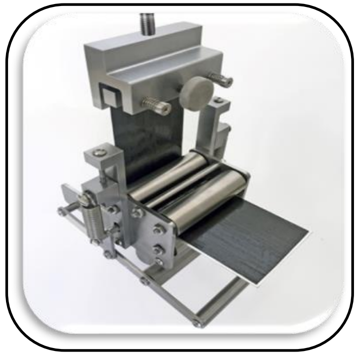
[1] Teagle, P.R. (1983). The quality control and non-destructive evaluation of composite aerospace components. *Composites, 14*(2), 115-128.

MATERIAL ACCEPTANCE – RESIN PROPERTIES

- *Total heat of reaction and Tg are indicators of DOC*
  - **ASTM E2160** - Heat of reaction using DSC
  - **ASTM E1640** – Tg using TMA
  - **ASTM E2602** – Tg using DSC
- *Mass loss indicates moisture absorption*
  - **ASTM E2008** – Thermogravimetric analysis (TGA)
- *Cure behavior can be observed*
  - **ASTM D4473** – Modulus of elasticity evolution using DMA
  - **ASTM D4440** – Viscosity using rheometer
  - **ASTM D2471** – Gel timer test (withdrawn 2008)



MATERIAL ACCEPTANCE – PREPREG PROPERTIES

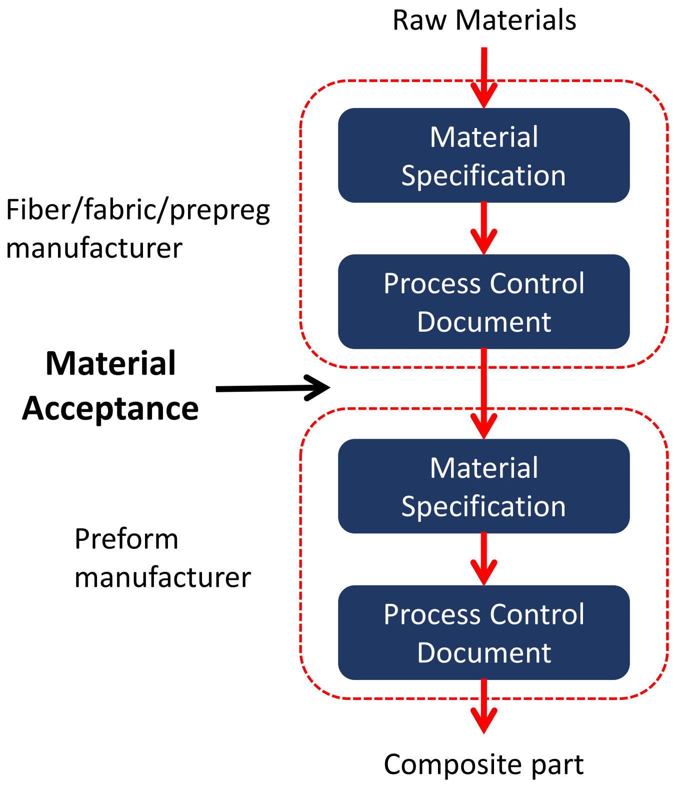


TACK

- Measuring adhesive force in prepreg/tool or prepreg/prepreg interfaces
- Peel test: ASTM D8336
- Used to determine parameters for AFP process

DRAPE

- Ability of the prepreg to be formed around tight radii and remain tacked for a specified period of time.
- Measured via bending stiffness tests
- Determines defects and non-conformity to the surface during hand-layup process



The simple assessment of prepreg properties against fixed acceptance standard has been superseded by statistical analysis of batch test results. [1]

[1] Adams, D. (2022). Composite prepreg tack testing. *Gardner Business Media, Inc.* https://www.compositesworld.com/articles/composite-prepreg-testing

MATERIAL ACCEPTANCE

Standard Prepreg and Cured Sample Tests [1]

Property	Test
Tensile strength, modulus, and strain	ASTM D 651 for resin ASTM D 3039 for composite
Poisson's ratio	ASTM E 132
Compressive strength, modulus, and strain	ASTM D 3410
In-plane shear strength, modulus, and strain	ASTM D 3518
Flexural strength and modulus	ASTM D 790
Impact toughness	ASTM D 3398
Fatigue	ASTM D 256 or user defined test
Density	ASTM D 1895
Thermal properties, including glass transition temperature, coefficient of thermal expansion, and weight loss at temperature	User defined
Chemical exposure to acetone, chlorinated solvents, oils, hydraulic fluids, jet fuel, body fluids, alcohol	User defined
Moisture effects	User defined
Flammability	User defined

Other Materials

- Curing Agent
- Catalyst
- Fillers and modifiers
- Consumables
- Cores


[1] Russell, J. D. (2001). Resin Properties Analysis. In *Composites* (pp. 679-681). ASM International.

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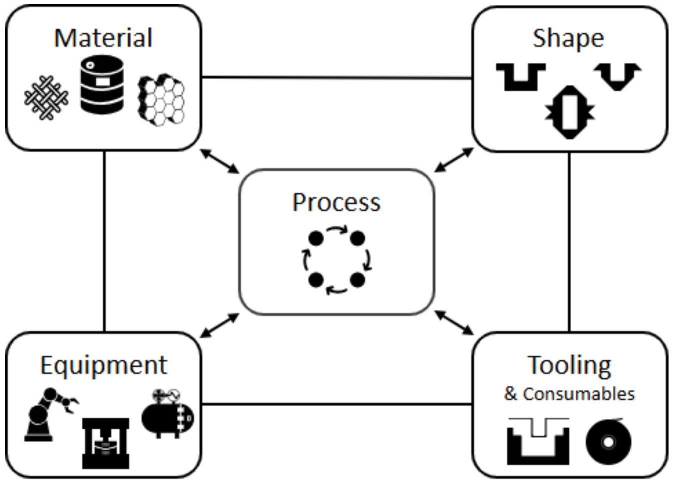
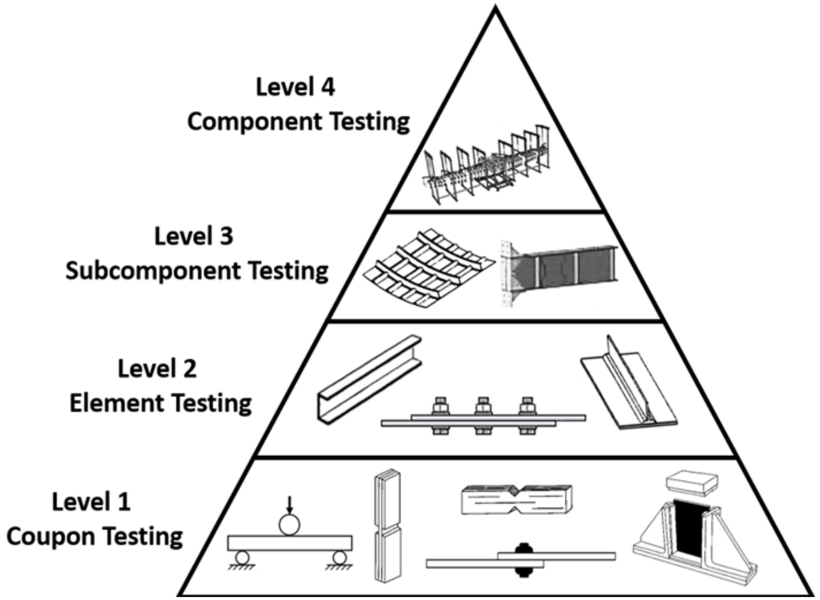
PROCESS SPECIFICATION

- Process specification documents include:
  - Material control
  - Materials and storage handling
  - Tooling
  - Facilities and equipment
  - Cure cycle
  - Process control specimens
  - Machining details
  - Manufacturing controls

The process specification can be developed using the building block method





PERSONNEL

- *‘Process Operators’* become *‘Process Owners’*
- Operators are typically educated about the problems associated with composite production
- Quality inspectors' jobs becomes less hands-on, now involves more:
  - Verifying compliance of engineering data
  - Random, periodic, in-process inspections
  - Tracking, verifying and tracing material certifications
  - Ensuring quality of tooling condition documentation
  - Operating specialized testing equipment (e.g. coordinate measurement machines, laser guidance/alignment systems)
- Even though high levels of automation are being used, the operator is still regarded as the greatest potential source of quality variation

Teagle, P.R. (1983). The quality control and non-destructive evaluation of composite aerospace components. *Composites, 14*(2), 115-128.

PROCESSES - TOOLING

- Key Quality Control (QC) Points
  - Documentation
    - Tool planning sheets, inspection records, tooling history tracking
    - Checkpoints for in-process inspections during fabrication
  - Master Models
    - Hand-Faired Models: verify geometric accuracy (ensure flatness, contour accuracy, surface quality, and reference system alignment)
    - Machined Models: verify geometric accuracy and alignment with specs
  - Second-Generation Patterns
    - Inspect for surface integrity, accurate reference lines, and proper alignment with updated configurations
  - In-Process Inspections
    - Verify coatings (e.g., release agent) and adhesion quality
    - Check for compliance with fabrication requirements and surface finish

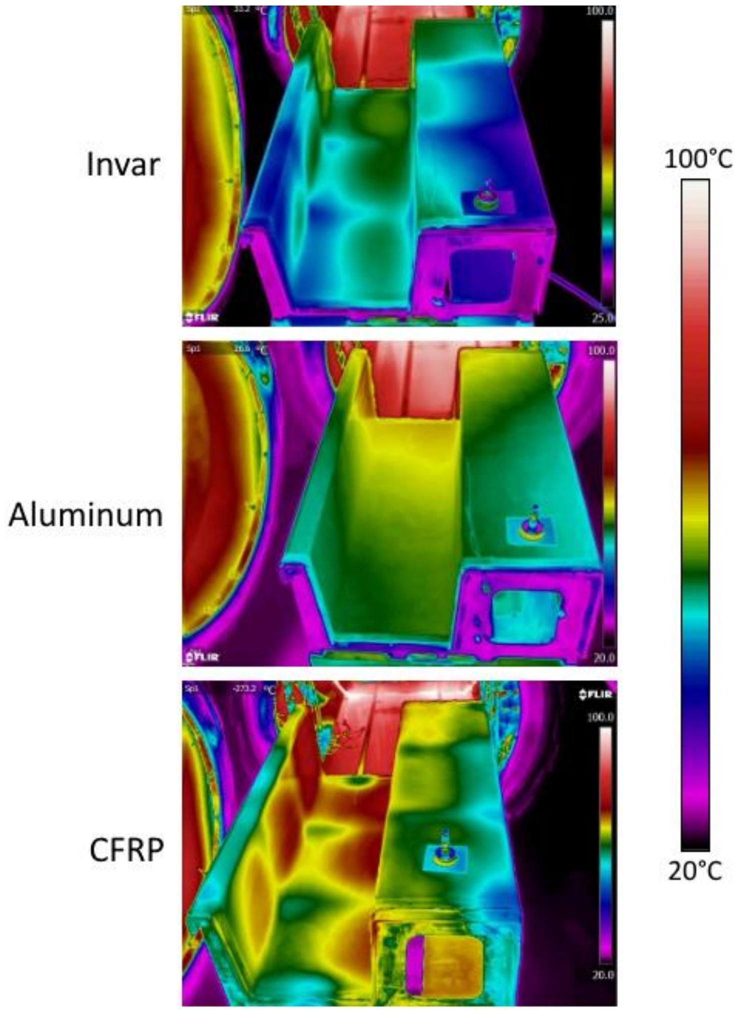
PROCESSES - TOOLING

Composite

- Advantages: Less expensive, lighter, lower thermal mass
- Inspections:
  - Dimensional accuracy (CMM, handheld tools)
  - Surface finish, scribe line depth, and uniformity
  - Vacuum integrity, thermocouples, and material certifications

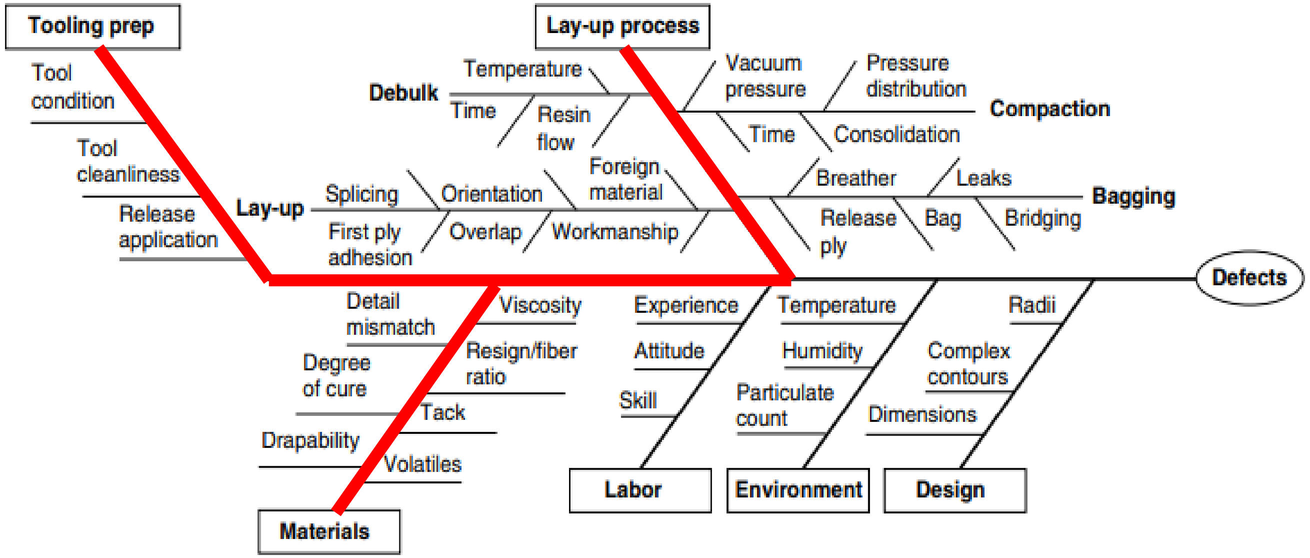
Metallic

- Advantages: Longer service life, higher dimensional stability
- Inspections:
  - Dimensional accuracy
  - Surface finish
  - Weld quality



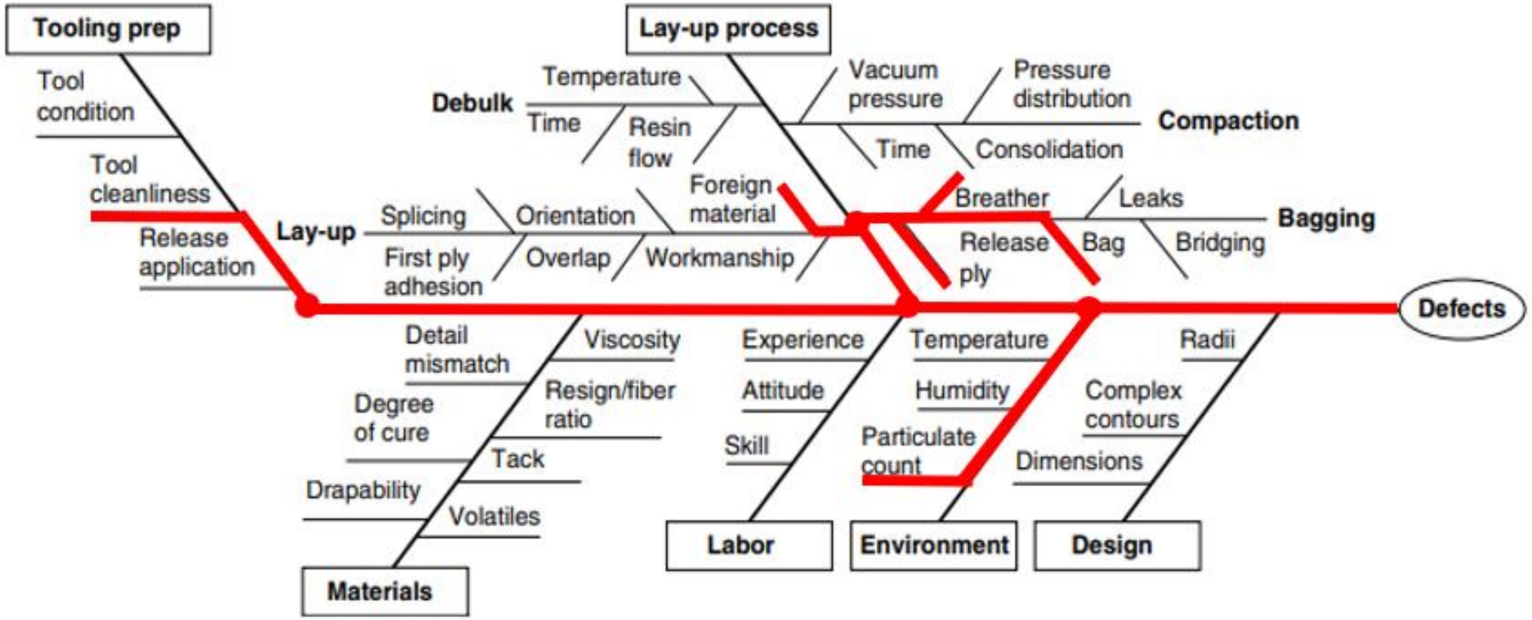
PROCESSES – LAYUP

- This diagram identifies key factors that contribute to defects in composite lay-ups
- Can be used to perform root cause analysis to determine which parameter needs to be controlled
- Root cause analysis steps:
  - Define the problem
  - Collect Data
  - Identify potential causal factors
  - Identify the root cause
  - Develop and implement solution
  - Monitor and sustain



PROCESSES – LAYUP – ROOT CAUSE ANALYSIS

- Example defect: Foreign object inclusions
- Possible causes:
    - Contamination during layup
    - Improperly cleaned tooling
    - Bagging material not removed completely
- Identify root cause by investigating each possible causal factor

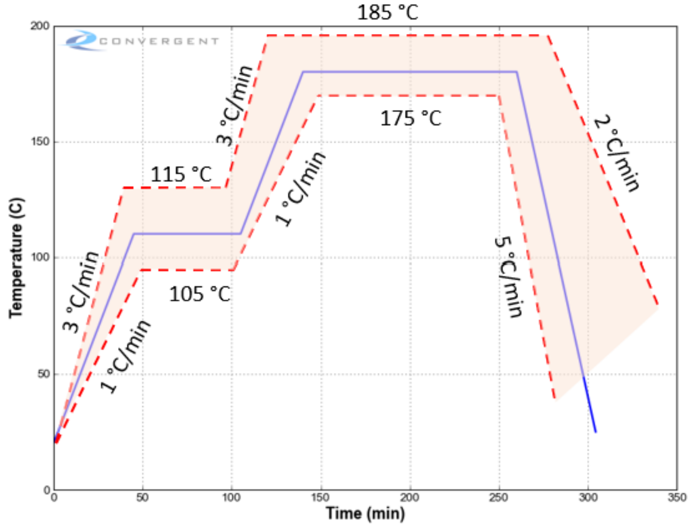


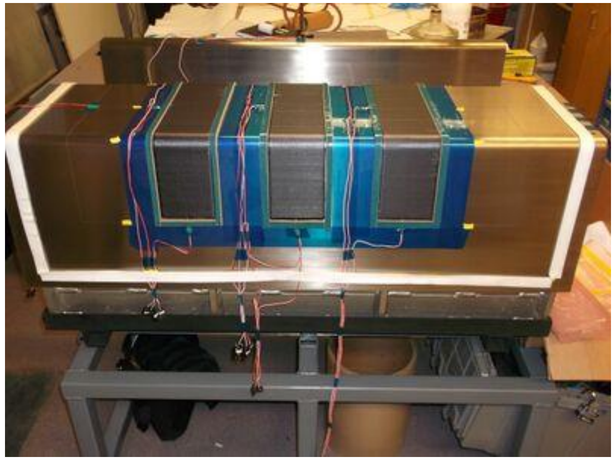
It is standard practice for inspectors to assess the component 'kits' before, during, and after layup. An essential part of this process is counting and re-recording leftover materials, such as backing paper and polythene trim. [1]

[1] Henson, G.A. (2001). Introduction to Quality Assurance.

PROCESSES – CURING

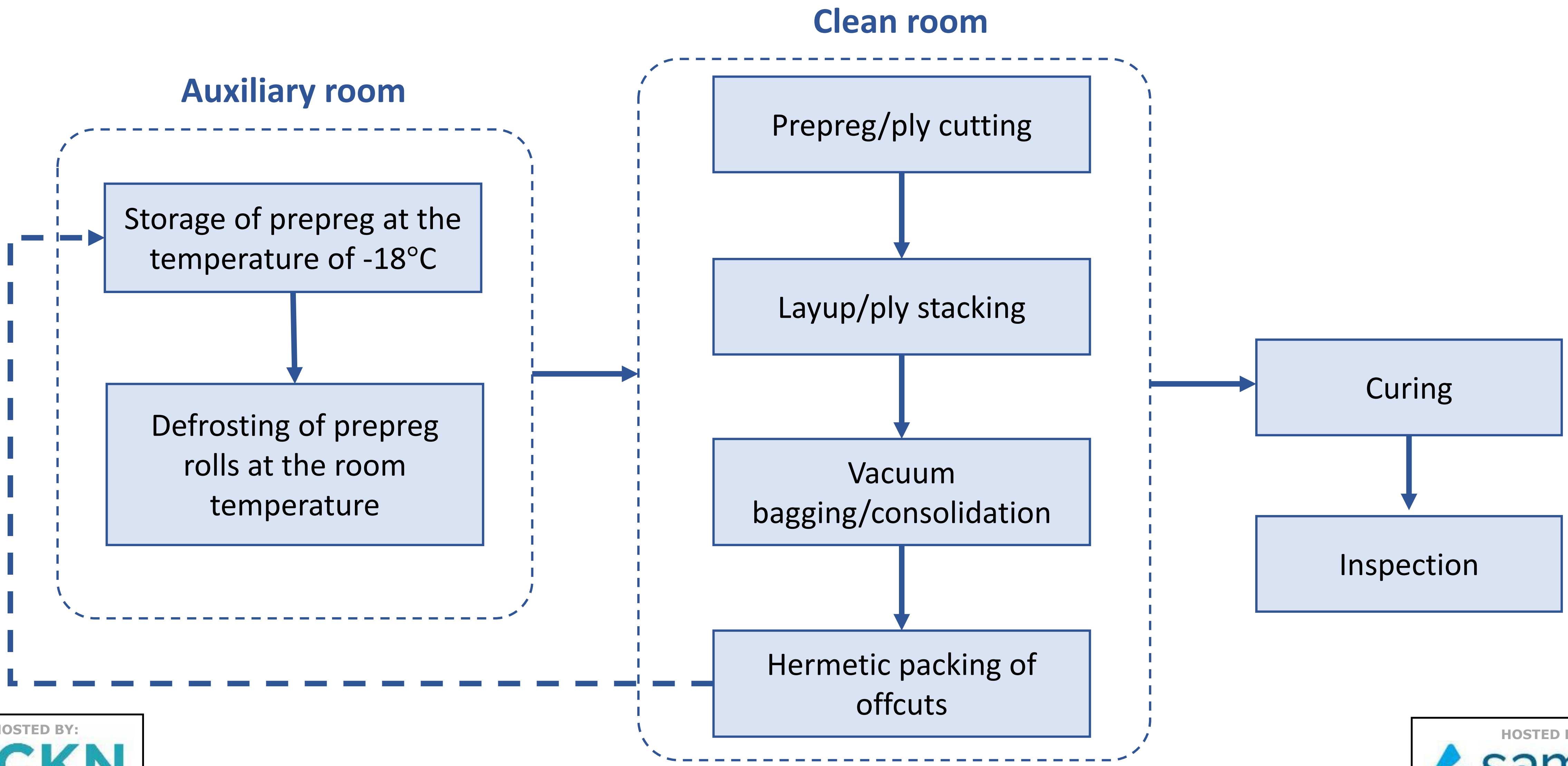
- The compliance to the cure cycle specs is typically verified through permanent records generated by the control instrumentation (thermal history)
- Temperature history
  - Temperature sensors (thermocouples) are often placed in different areas of the tool or curing chamber
- Pressure history
  - Pressure control ensures the resin is fully infused into the fiber mat, removing voids that could compromise the part’s strength
- Cure cycle specifications
  - The time at which the material is held at a specific temperature (cure time) is as important as the temperature itself.
  - Some composites require post-curing, where the material is heated at a lower temperature for a longer duration
- Moisture content management
  - Some materials should be degassed





Early planning in tooling and part design is essential to integrate sensors effectively

GENERAL DIAGRAM OF MANUFACTURING WITH PREPREG



[1] Szymański, Z. (2017). Quality control process of manufactured composite structures. Prace Instytutu Lotnictwa, (1 (246), 95-103.

CONSIDERAITIONS - PREPREG

- Defrosting pre-impregnates at room temperature (24-48 hours) requires the plastic bag to remain sealed until the material reaches ambient temperature to avoid condensation and potential delamination
- Quality control includes checking if the bag was unsealed and recording the date, time, and ambient temperature during defrosting

Material History Log

Material:		**Received From:**		**Source #:**	
Amount:		**Length (if applicable):**		**Width (if applicable):**	
Other Identification:					
Material Shipped	Date:		Time:		
Material Received	Date:		Time:		
	Net Travel Time:				

Date	Time Removed	Time Returned	Net Time Out (hrs)	Total Time Out (hrs)	Amount to Start	Amount Taken	Amount Left	Operator

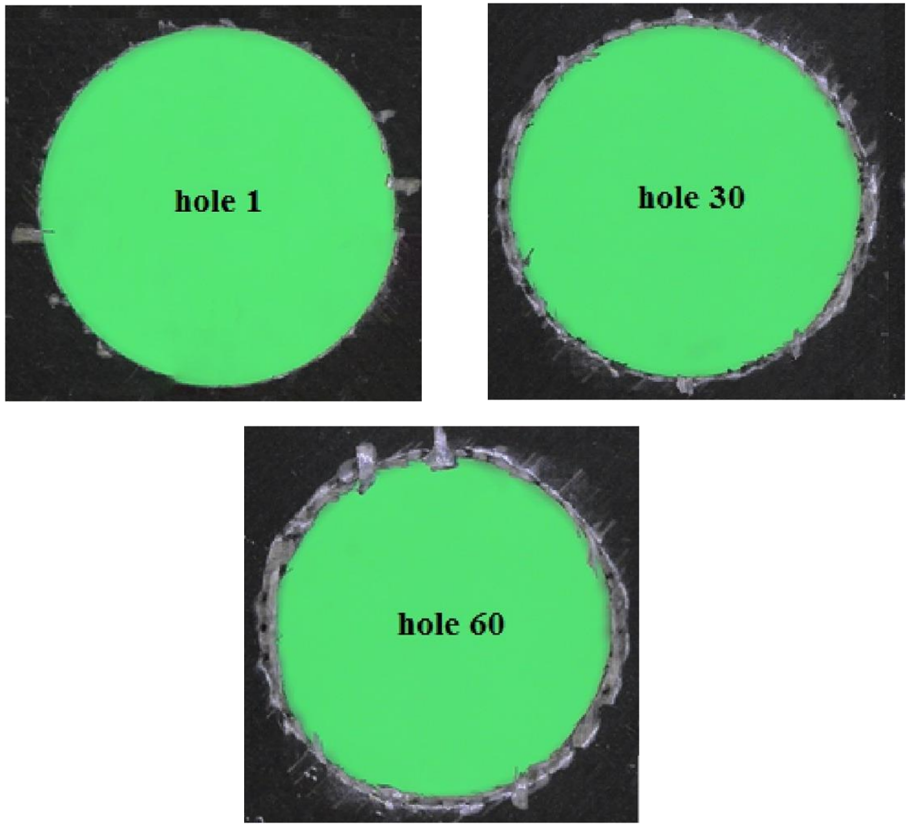
Example of material history log

Name:	
Date Removed:	
Material Type:	
Source Number:	

Example of prepreg cutout label

PROCESSES – MACHINING

- Abrasiveness of FRPs result in high tool wear rates, which lead to increased cutting forces and negative impacts on the surface quality of the workpiece
- **Material-Specific Challenges**: Traditional metal machining methods can cause delamination, fiber pullout, or surface damage in composites, specialized tools and precise cutting parameters are essential *(Source: CompositesWorld)*
- **Tool Selection**: Diamond or carbide-tipped tools, polycrystalline diamond (PCD) cutters, and CVD-coated end mills help reduce defects and improve tool life, tools with sharp edges and compressive helix designs prevent uncut fibers and delamination *(Source: Sandvik Coromant)*
- **Cutting Tool Tracking:** tracking tool use is essential part of ensuring quality machining outcomes



Optical microscope images of CFRP drilled hole quality degradation with growing tool wear (6000 rpm–0.20 mm/rev) [1]

[1] Figures adapted from Fleischer, J., Teti, R., Lanza, G., Mativenga, P., Mohring, H., & Caggiano, A. (2018). Composite materials parts manufacturing. *CIRP Annals, 67*(2), 603-626.

PROCESSES – ASSEMBLY

- **Key QC Focus Areas**
  - **Hole Drilling**
  - **Process Improvements**:
    - Co-curing and co-bonding laminates
    - Liquid moulding development
    - Self-aligning designs
- **Simplifying Assembly**
  - DFMA (Design for Manufacturing and Assembly)
- **Process Monitoring**
  - Real-time statistical process control at operator level
  - Non-intrusive monitoring with corrective measures at key points

INSPECTION

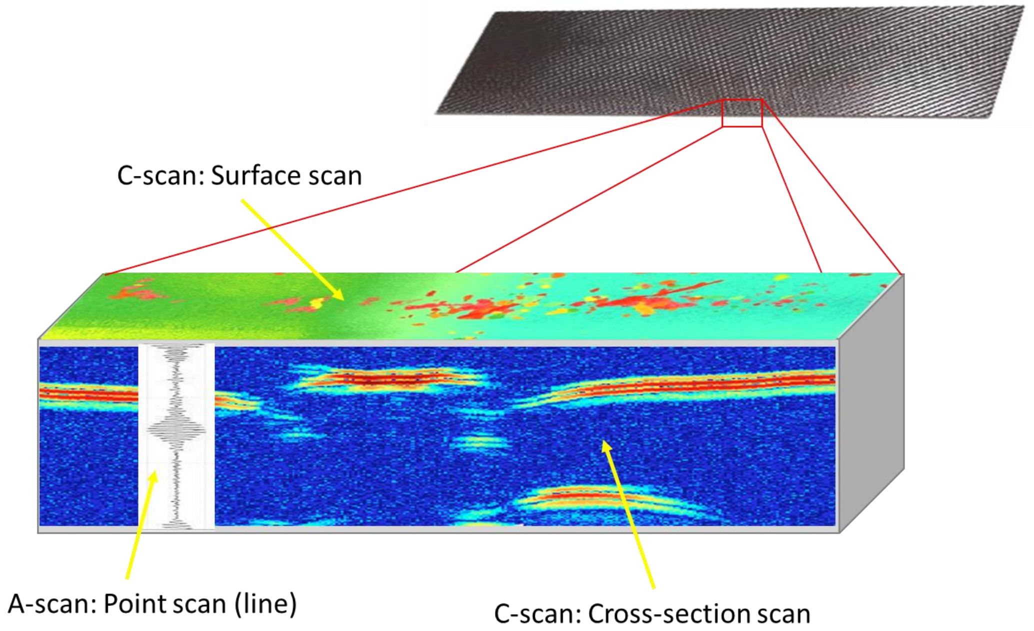
- Coupon level
  - Coupons for mechanical testing are made during the process
    - Flexural, interlaminar shear, volume fraction are common
- Component level
  - The component itself is tested/inspected
  - Could be destructive or non destructive
    - Voids, delamination, disbonding, foreign object inclusions
- Non-destructive testing is commonly used

NON-DESTRUCTIVE TESTING

- Benefits of NDT
  - Ensures composite quality without damage and with minimal waste.
  - Provides traceability and supports process analysis.
  - Informs decisions on nonconforming parts (e.g., rework or accept-as-is).
- Key NDT Methods
  - Visual Testing
  - Ultrasonic Testing
  - Radiographic testing
  - Thermography
  - Acoustic emission
- AIM Webinar about NDT: https://compositeskn.org/KPC/A366

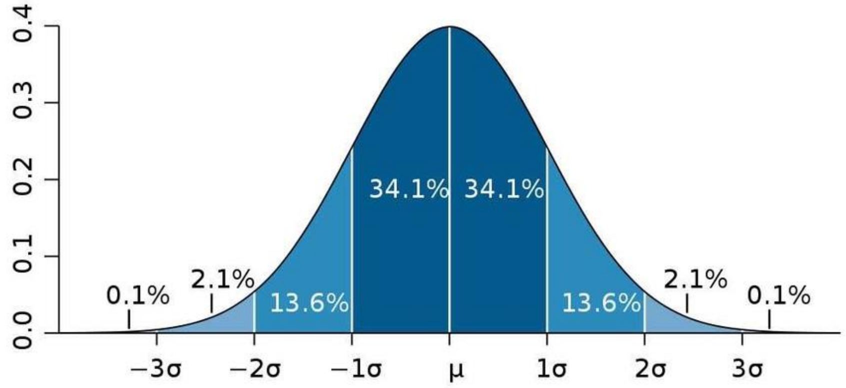
Challenges in NDT of Composites

- Anisotropy
- Multiple failure modes
- Complex geometries and variable thickness
- Subtle defects, micro-cracks or delamination



STATISTICAL PROCESS CONTROL (SPC)

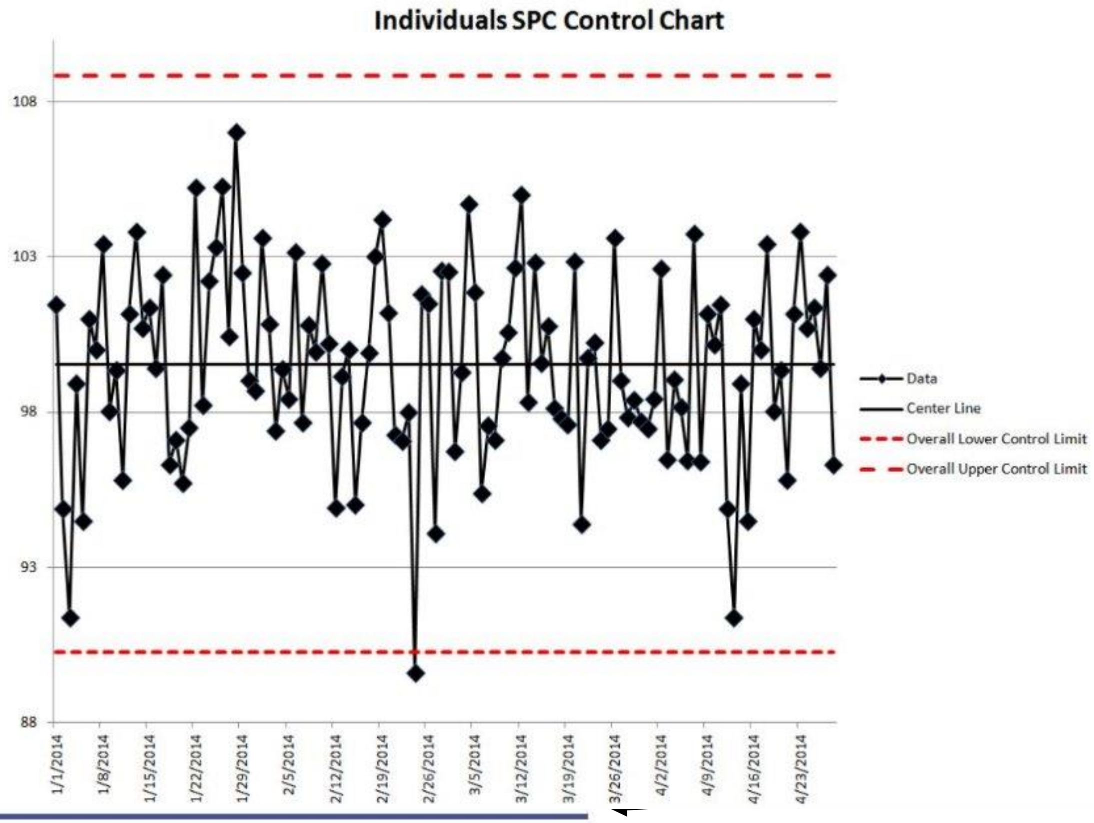
- Allows manufacturers to distinguish between deterministic vs. random factors
  - **Chance** variation result from specific, identifiable factors, is **inherent** in process, and **stable** over time, and **assignable**
  - **Uncontrolled** variation, arises from unpredictable or unknown sources, which is **unstable** over time - the result of specific events outside the system.
- Understanding dispersion is critical to the management of industrial processes
- SPC is particularly valuable for analyzing deviations in process parameters, temperature, pressure, and machinery attributes that affect scrap rates

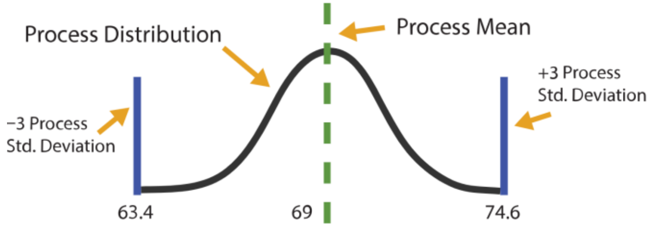


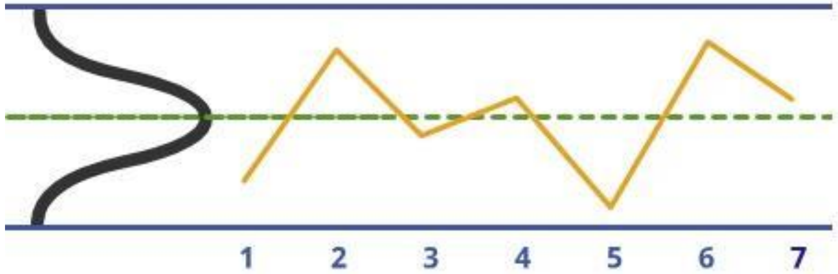
[1] https://news.mit.edu/2012/explained-sigma-0209

CONTROL CHART SERIES

- Key SPC tools:
  - Acceptance sampling: helps decide whether to accept an entire production lot
  - Descriptive statistics: describes quality characteristics and relationships of finished goods
- Improve Performance
  - Run charts: plot a single value over time
  - Control charts: track data within upper and lower control limits
  - Time series analysis: provides insights to refine processes and improve performance

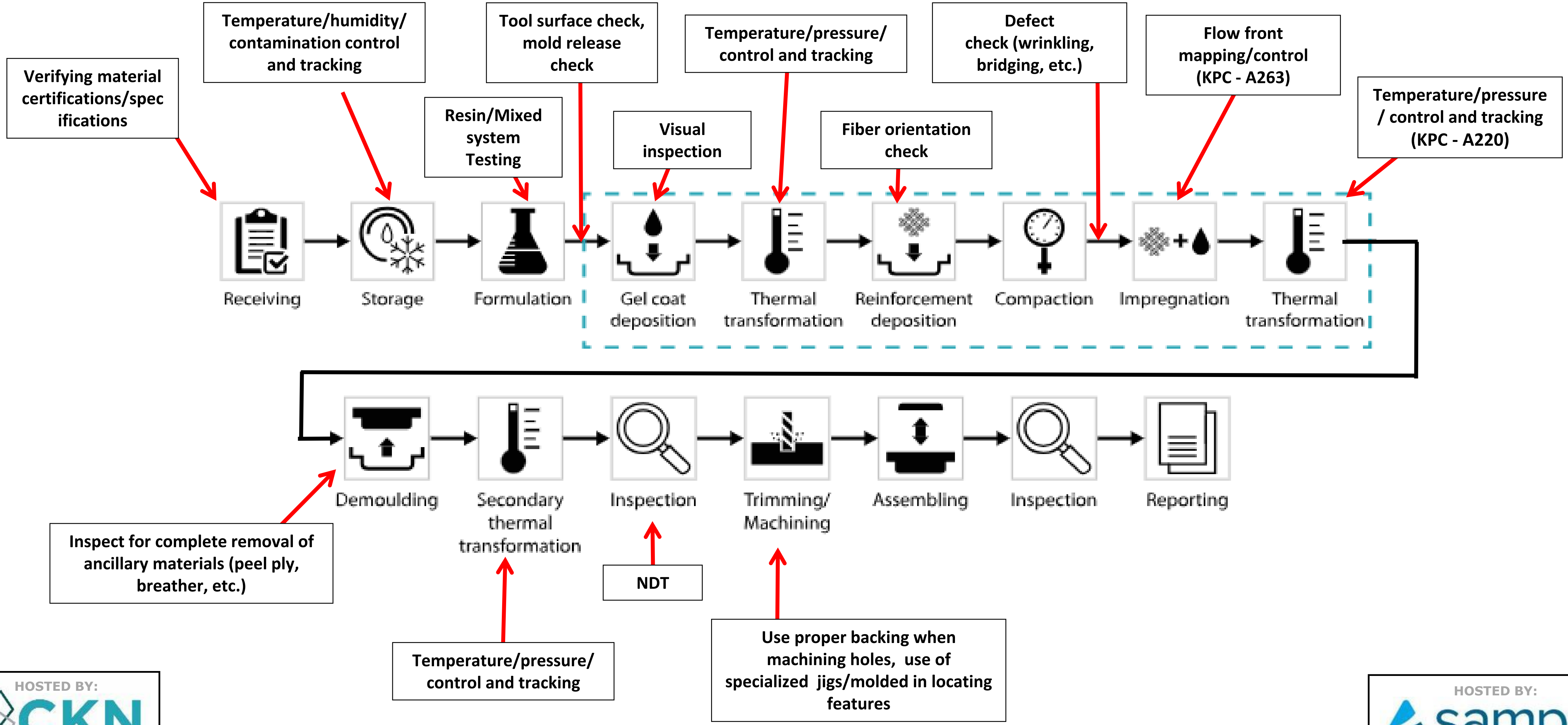






[1] https://www.moresteam.com/toolbox/statistical-process-control
[2] https://www.leansixsigmadefinition.com/glossary/statistical-process-control/

EXAMPLE – VACUUM ASSISTED RESIN TRANSFER MOULDING



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CONCLUSION

- Factors affecting quality of composite parts:
  - Raw material quality
  - Manufacturing process
  - Inspection process
- Various approaches to assess and monitor quality:
  - Testing
  - Inspection
  - Statistical analysis
- Threats/opportunities at each step

Thank you for joining us!

Keep an eye out for upcoming AIM events:

Cure and Thermal Management Considerations of Thermoset Composites

Hosted by Dr. Casey Keulen
March 26, 2025
https://compositeskn.org/KPC/A379

And don't forget to visit the KPC for more information:

https://compositeskn.org/KPC

Today's Webinar will be posted at:
https://compositeskn.org/KPC/A378