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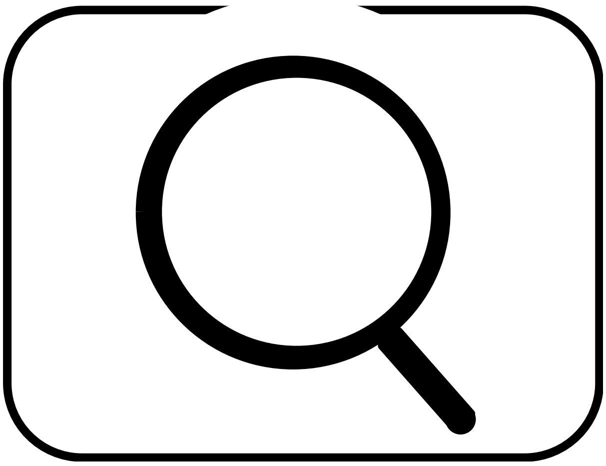
P142

Troubleshooting tooling to achieve part quality

Practice document



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Prerequisites	• Effect of tooling in a thermal management system

Q: "My tooling for a given type of part is the same style as used for similar parts around the world but the prepreg system chosen has a different resin chemistry compared to that used for every other part like this. The tools do not function in the same way (excessive flow) and do not provide good quality parts."

A: It is likely that the change in resin chemistry has altered the flow characteristics of the material. The thermal history imparted onto the part by the tool may be inappropriate for this new resin system. The tool influences the part's temperature and, therefore, its viscosity. For this new resin system, the viscosity has likely decreased, allowing for excessive resin flow which may lead to dry spots, poor resin volume fraction, and increased porosity. To combat this, the part temperature can be kept lower until the cure reaction has progressed sufficiently. This will prevent the viscosity from decreasing to the same extent, thereby reducing flow. From a tooling standpoint, one way to do this is to implement a tool with a larger thermal mass. As a result, both part and tool will take longer to heat up and the viscosity will not drop excessively. Once the cure reaction has advanced sufficiently, an increase in temperature of the part will not reduce the viscosity. It's possible that after the switch in resin chemistry, the tool's thermal mass was insufficiently low to keep the part from heating quickly, resulting in a significant initial drop in viscosity which allowed for increased flow. If the tools are preheated, an increase in thermal mass of the tool may be insufficient to delay part heat up. In that case, alterations to the cure cycle may have to be implemented, such as implementing a relatively low temperature isothermal hold until the part has cured sufficiently to prevent a significant drop in viscosity. To learn more about flow considerations, visit ensuring appropriate resin flow and part consolidation for a new material.

Overview[edit | edit source]

Tooling plays an important role in determining part quality. This may include providing shape to the part, influencing the part's thermal response, providing a good surface, and/or distributing pressure onto the part (particularly in the case of two sided tooling). Changes in tooling may have a profound impact on part quality. Understanding what to look for and how to troubleshoot tooling to achieve quality metrics is important.

Thermal management considerations[edit | edit source]

Link to thermal management

To gain a deeper understanding of how tooling may influence the thermal response of parts, visit the following page, effect of tooling in a thermal management system.

Generally speaking there are two ways in which in which tooling influences the part temperature. These are:

1. By acting as a heat source/sink
2. By influencing airflow, and therefore the heat transfer coefficient (HTC) - applicable only in convective heating systems

Tooling as a heat source/sink[edit | edit source]

During heat up in a convection system, heat may be transferred to the part via its bagside and/or toolside interface. In the case of two sided tooling (such as in a hot press), heat must come from the tooling. This means that the tooling always leads the part in temperature during heat up. If heat flows through the tool into the part, the tool behaves as a heat source with respect to the part. Once the part exotherms, however, the part often leads the tool in temperature, and heat flows from the part through the tooling. This is true for both conductive and convective heating environments. At this point, the tool acts as a heat sink, drawing heat away from the part and expelling it to the environment. The ability for tooling to be able to act as an efficient heat source or heat sink as needed is crucial for ensuring part quality.

If the tool can absorb a lot of the thermal energy (i.e. has a high thermal mass), it will heat up slowly. This will impact the heat up rate of the part and, in turn, lengthen the cure cycle time and potentially introduce large temperature gradients throughout the part. Conversely, if the tool cannot absorb a lot of energy (i.e. low thermal mass), although it may heat up quickly, when the part exotherms the tool may not be able to absorb the generated heat. As a result the part may thermally degrade.

The energy required to heat the tooling is determined by its thermal mass, as governed by the following equation:

$Q=mC_p\Delta{T}$Energy required to raise an object's temperature, where Q = energy, m = object mass, C_p = specific heat capacity, Δ{T} = change in temperature from applied energy. Note that mC_p is the thermal mass of the object.

Aside from the tool's ability to absorb energy, the thermal conductivity and diffusivity of the tool also matters. If the tool has a low thermal mass but also a low thermal diffusivity, then it may heat up quickly, but unevenly. This will again affect the manner in which the part heats up as well. During exotherm, a tool with a higher thermal conductivity and diffusivity will help in conducting heat away from the part and out to the surrounding environment. In that sense, a tool with a relatively low thermal mass but high conductivity/diffusivity (such as aluminum) may still act as an effective heat sink. Another aspect to consider is that different areas of the tool/part may heat up at different rates, due to thickness changes and other local features. Tools with a high thermal diffusivity will help alleviate temperature gradients arising from such features. -tooling material

Thermal diffusivity can be calculated using the following equation:

$\alpha=\frac{k}{\rho C_p}$Thermal diffusivity, where α = thermal diffusivity, k = thermal conductivity, ρ = density, and C_p = specific heat capacity.

The tables below provide a quantitative and qualitative list of typical thermal properties for tooling materials. Properties for composite tools are dependent on the fibre volume fraction and orientation. Note that in the second table, high and low thermal mass are shaded both red and green. The reason for this is that either can be beneficial or detrimental. A high thermal mass increases thermal lag and heat up time, but it decreases part exotherm. A low thermal mass decreases thermal lag and heats up quickly, but increases part exotherm.

Typical material properties for tools. Note that the properties for the composite tool are dependent on the fibre volume fraction and orientation.

Tooling material	**Density (kg/m^3)**	**Specific heat capacity (J/kg-K)**	**Thermal conductivity (W/m-K)**	**Coefficient of thermal expansion - CTE ($x10^{-6}$/°C)**	**Thermal diffusivity ($x10^{-6}m^2/s$)**
Invar	8000	515	11.0	0.6-1.5	2.67
Mild steel	7850	510	55	11	13.7
Carbon-epoxy composite	1580	870	0.7 (through-thickness)	-0.5 (in-plane) 22.5 (through-thickness)	0.5 (through-thickness)
Aluminum	2710	896	167	23	68.9

Qualitative comparison of tooling materials

Tooling material	**Cost**	**Durability**	**Weight**	**Thermal mass**	**Thermal conductivity**	**Coefficient of thermal expansion (CTE)**	**Thermal diffusivity**
Invar	$$$	Excellent	Heavy	High	Moderate	Low	Low
Steels	$$$	Excellent	Heavy	High	Good	Moderate	Moderate
Composites	$	Low	Light	Low	Low	Moderate	Low
Aluminum	$$	Good	Moderate	Low	Excellent	High	High

Tooling influence on airflow[edit | edit source]

In a convective heating environment, the shape of the tooling can influence airflow over one part or multiple parts (if multiple parts are cured at the same time for example). By redirecting airflow, the local heat transfer coefficient (HTC) changes. Aside from HTC changes across the part, the HTC across complex tooling is also likely not uniform. Various features of the tool may experience different levels of airflow. By influencing the HTC, the heat up and cool down rate of the tool/part is affected. To learn more, visit the following page.

To learn how to measure airflow and the HTC, visit the following pages:

- How to measure airflow in a thermal system
- How to simulate airflow in a thermal system
- How to experimentally determine the HTC
- How to back calculate the HTC using simulation

Troubleshooting steps[edit | edit source]

Below is a list of some thermal management troubleshooting steps that may be performed to determine the effect of tooling on part quality.

1. List the defects observed in the parts[edit | edit source]

This includes any observations where the part is not meeting quality metrics.

2. List changes to the tooling that were performed[edit | edit source]

This may include changing the tooling material, shape, thickness, etc. Have the thermal properties of the tool been altered (i.e. thermal conductivity, diffusivity, specific heat capacity, density, etc.)? Did the changes increase or decrease the thermal mass of the tool? Answering these questions and relating them to the observed defects may help identify the reason for the defects. To understand how changes to the tooling may have influenced the part's thermal response, visit the following page: effect of tooling in a thermal management system.

3. Determine the lead/lag locations on the tool[edit | edit source]

Determining the lead/lag locations often relies on engineering judgement. A good place to start is the thickest and thinnest areas of the tool, where the thickest likely represents the highest lag and thinnest the highest lead. It's also possible that a single location may represent the highest lead and highest lag location. If possible, this step should be performed on both the previous tool as well as the new tool.

4. Use these locations for proxy thermocouples[edit | edit source]

Measure the temperature at the suspected lead/lag locations (or other potential lead/lag locations) using thermocouples. The temperature measured at these points can be used as a proxy for the minimum and maximum part temperature. If the temperature at these locations on the tool are outside the bounds of the temperature specifications for the part, then it can be assumed the part is not meeting its thermal requirements. Note the time when the minimum and maximum temperatures occur. It may be that the maximum temperature occurs during exotherm of the part. If so, this implies the tooling is unable to absorb the heat or is inefficient in dissipating the heat to the environment. If possible, this step should be performed on both the previous tool as well as the new tool. That way the two results can be compared. If the new tool doesn't meet temperature specifications for the part while the old tool does, then it is likely that the change in tooling is indeed responsible for temperature-related defects in the part.

Additional thermocouples should also be placed at various other locations on the tool to get an idea of the thermal gradients across the tool. Again, a similar step should be taken with the old tool. If the gradients in the tool have changed significantly, this may induce a different thermal response in the part and could also lead to residual stress-induced deformations.

5. Correlate part quality to location on tool[edit | edit source]

Are the observed defects occurring at specific locations consistently and do these locations match with the lead/lag locations of the tool? If yes, this further assures that the min/max temperature of the new tooling is negatively impacting part quality. If no, measure the tool temperature in the affected areas to get an idea of the tool temperature where the part defects are occurring.

6. Implement tooling mitigations[edit | edit source]

Thermal mitigation strategies for tooling

Problem/defect	Mitigation strategy
Maximum temperature too high	• Ensure good airflow across this area of the tool (convective heating) • Ensure good contact in this area with the heat source (conductive heating) • Increase local tooling thickness in this area • Change tooling material to one with higher thermal mass • Change tooling material to one with higher thermal conductivity/diffusivity
Minimum temperature too low	• Ensure good airflow across this area of the tool (convective heating) • Ensure good contact in this area with the heat source (conductive heating) • Decrease local tooling thickness in this area • Change tooling material to one with lower thermal mass • Change tooling material to one with higher thermal conductivity/diffusivity
Uneven temperature/large thermal gradients across tool	• Ensure good airflow across the tool (convective heating) • Use tooling with an open substructure (convective heating) • Ensure good contact with the heat source (conductive heating) • Change tooling material to one with higher thermal diffusivity

Material deposition management considerations[edit | edit source]

Link to material deposition management

Content coming soon

Flow and consolidation management considerations[edit | edit source]

Link to flow and consolidation management

If changing the tooling influences the flow characteristics of the part, it is likely the viscosity evolution of the part has changed due to an altered thermal profile. To learn about ensuring appropriate resin flow, visit the following page: ensuring appropriate resin flow and part consolidation for a new material.

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

Link to residual stress and dimensional control management

The coefficient of thermal expansion (CTE) is another factor that should be considered when changing tooling material. If the mismatch in CTE between the tool and part is considerable, and this is not mitigated for, then the part may deform during cure or upon demoulding. The best way to mitigate for this is to match the tool CTE with the part CTE. Generally speaking, composite materials have a low CTE while metallic tools have a much higher CTE. The exception is invar, which has a very low CTE and is therefore a preferable option for advanced tooling choices. However invar is also very expensive, heavy, and thermally massive. Composite tools, may also offer a close match in CTE to composite parts. However, because the resin and fibres of a composite material exhibit different CTEs, the overall CTE for a composite part is dependent on the fibre volume fraction and orientation of the fibres. Therefore, it can't be assumed that all composite parts, even if made with the same materials, have the same CTE. The same is true for composite tooling.

Another way to mitigate CTE-induced deformation at the tool-part interface is to include a low-friction film between the two surfaces. This may be a release agent, release film, teflon film, or other consumable.

General CTE values for common tooling materials are provided in the table below:

CTE values for common tooling and part materials [1][2]

Material	CTE ($x10^{-6}$/°C)
Aluminum	23
Steel	11
Invar	0.6 to 1.5
Epoxy	45 to 62
Polyester	60 to 200
Vinylester	100 to 150
Carbon fibre (longitudinal)	-0.2 to -0.5
Carbon fibre (transverse)	10 to 15
E-glass fibre (longitudinal)	5
E-glass fibre (transverse)	5

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References

1. ↑ [Ref] Daniel, Isaac M.; Ishai, Ori (2006). *Engineering Mechanics of Composite Materials*. Oxford University Press. ISBN 978-0-19-515097-1.
2. ↑ [Ref] MatWeb LLC. "MatWeb: Online Materials Information Resource". Retrieved 9 September 2020.

About **Help**

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.

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.

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

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

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

A quantitative measure of how a material will respond to transient thermal conditions. It is defined as the ratio of thermal conductivity to the volumetric heat capacity of the material (density times the specific heat capacity).

Materials with large thermal diffusivity have a high thermal conductivity relative to their capacity to store energy (heat capacity) and will rapidly distribute the thermal energy throughout its volume and rapidly change temperature to reach the new equilibrium temperature.

Materials with small thermal diffusivity have a low thermal conductivity relative to their capacity to store energy (heat capacity) and will have a sluggish temperature response to a change in thermal conditions (large temperature lag). This is because it takes more energy per unit volume to change the temperature, and the low thermal conductivity means it takes longer to distribute the thermal energy throughout its volume.

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.

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.