ABSTRACT

Tooling decisions have a significant impact on the thermal response of composites manufacturing systems at multiple scales. Current typical practices for tool design often overlook the consequences of these tooling decisions on thermal management outcomes. Whereas this may have been adequate to date, increasing expectations such as faster cycles, or larger and more complex parts, requires better future practice. For instance, at a global scale, tool substructure design and orientation can affect airflow and heat transfer coefficient distributions in autoclaves and ovens. At a local scale, material selection and geometric features of the tool, such as the facesheet thickness and its construction, can influence the temperature profiles of parts, and thus the ability to satisfy process specifications. In this paper, we discuss experimental and simulation based methods that can be used to evaluate and understand these effects. Experimental thermal profiling and predictive modelling results for small-scale but industrially relevant Invar, aluminum and composite tools, with nominally identical geometry, are presented and discussed. This work highlights broader efforts to formalize science based composites manufacturing practices to reduce manufacturing risk, cost and development timeframes.

INTRODUCTION

The thermal management of composite parts during processing is critical to ensure material equivalency and acceptable part producibility [1–3]. Experimental thermal profiling represents current typical practice that involves experimental measurement of part heat-up rates and temperatures using thermocouples (TCs). The manufacturing science for thermal management problems is relatively well understood, particularly heat transfer for autoclave and oven curing process and resin cure kinetics. Typically, the thermal response of curing laminates is dependent on the interaction of Equipment–Tool–Part–Material (ETPM) manufacturing system attributes: 1) the internal heat generation of parts (material); 2) the thermophysical properties of parts and tools; and 3) the airflow around and between parts, tools and equipment (Figure 1).

Despite our science-based understanding of these problems, many current composites manufacturing practices still rely strongly on engineering judgement, experience and methods of ‘trial and error’. Consider current tooling design practices: according to an informal survey of tooling manufacturers at recent SAMPE and CAMX conferences [1, 3], tooling decisions are most often driven by cost, durability and dimensional control requirements. Few datasets of production-scale size and relevance exist in the literature that discuss the implications of tooling decisions on thermal management outcomes such as lead/lag temperatures, heating/cooling rates and cure advancement. If not appropriately managed, these
outcomes are in themselves the cause of cure cycle non-conformances resulting in the rejection of parts. They may also detrimentally affect downstream quality and residual stress and dimensional control outcomes, such as wrinkling and porosity due to insufficient resin flow, or process-induced delaminations due to excessive residual stress development. As expectations grow, for example the desire for faster cycles, or larger and more complex parts, or more heavily and diversely loaded autoclaves and ovens, the need to more effectively manage composites manufacturing risk becomes paramount.

In this paper, we discuss experimental and simulation based methods that can be used to understand and evaluate these effects at both global and local scales, and strategies that should be considered as part of robust tool design for thermal management. Case studies, in which experimental and predicted modelling results for three small-scale Invar, aluminum and composite tools with nominally identical geometry are presented. These findings will support the development of science based guidelines for thermal design of tools and associated heating equipment design. This work is part of a broader initiative to establish a knowledge framework that aims to integrate composites manufacturing science (‘know-why’) with manufacturing experience (‘know-how’) [1–3].

**Role of Tool Decisions on Thermal outcomes**

**Global Effects: Airflow and Heat Transfer Coefficients**

As described earlier, thermal management in composites processing is a manufacturing systems problem. Tooling decisions can affect this response at both global and local scales. At the global scale, these decisions relate to the interaction between equipment and tools. For convective heating systems, such as autoclaves and ovens, the airflow pattern and velocity around the tool creates hot and cold zones, or thermal lag distributions, across the tool surface. This effect, and the role of the heating system, is
usually lumped and represented at the boundary of the tool by heat transfer coefficients (HTC). This approach, however, poses challenges considering the many parameters that may influence HTC values. This includes equipment design, tool geometry and substructure configurations, tool nesting and loading scenarios, such as a single tool in a dedicated load versus multiple tools in a batch load. These parameters can be systematically studied by conducting experiments or via numerical analyses. In one study, for example, airflow in a floor air duct autoclave was simulated using computational fluid dynamics (CFD) as shown in Figure 2 (small-scale autoclave of about 2 m length and inlet velocity of 10 m/s [4]). For this simulation, ANSYS Fluent software with a K-epsilon turbulence model was used. Simulation results for two cases: 1) an empty autoclave; and 2) an autoclave loaded with a single steel tool are compared in Figure 2. This comparison shows a low air velocity zone near the autoclave door when the tool is loaded. Simulation also shows that toward the back of the autoclave, airflow velocity is higher than the front of the autoclave. This suggests higher HTC values and therefore lower thermal lags if the tool were placed further away from the autoclave door (in this instance). This simple analysis also highlights the complex nature of the interaction between equipment and tools, and their influence on the thermal response.

A similar approach can be taken to investigate the effect of substructure design. Consider two steel tools with similar facesheets but different substructure designs, open versus closed, as shown in Figure 3. Here, both tools were placed in a virtual wind-tunnel with a uniform inlet velocity of 6 m/s. The airflow pattern around these tools was predicted using ANSYS Fluent as shown in Figure 3 [4], with higher air velocities observed under the open substructure tool. Since a closed substructure blocks the airflow under the tool, clearly it reduces the heat flux and HTC at the bottom of the tool compared to the open substructure tool. Aside from affecting the airflow pattern, substructure also increases the tool surface area, increasing heat flux to the part, and adds thermal mass to the tool, thus decreasing heat flux to the part. These opposing mechanisms further contribute to the creation of hot and cold zones on the tool surface. Figure 3 also shows a comparative heat transfer analysis between the two tools. Using ANSYS, a constant heat flux of about 3.6 kW/m² was applied to the top surface of these respective tools [4]. At a given time, representing a transient steady-state heat-up condition, the difference between open and closed tooling sub-structures, in terms of peak temperature and spatial temperature pattern,
is observed.

Tool placement or nesting [5] in the autoclave is another important factor that can influence the airflow pattern and HTCs around tools. This correlation becomes more complicated when considering scenarios, such as single tool loading versus multiple tool loading, and the effect of loading racks. Thermal analysis of the system, using coupled CFD-heat transfer analysis or experiments, can be used to understand these complex behaviours. However, current thermal simulation approaches often rely on uniform HTCs rather than conducting CFD analysis or experimentally measuring HTC distributions. It is important to understand the impact that these simpler boundary conditions have upon the simulation validity. Experiment driven zone-based boundary conditions have been suggested instead of idealized uniform boundary conditions [6]. Additionally, based on the relationship between HTC and fluid velocity, engineering solutions can be developed to alter the flow pattern within a heating system to normalize the fluid velocity across the tool surface, in effect, normalizing HTCs. This would improve the overall surface thermal uniformity.

Local Effects: Material Selection and Geometric Features

At the local scale, tooling design details also affect the thermal management of curing laminates. These effects include tooling materials selection, facesheet thickness and its construction and geometric features, such as localized pad-ups. The effect of tooling materials is described later in a case study while comparing the thermal responses of a family of three small-scale tools with similar nominal geometries but fabricated from typical tooling materials: Invar, aluminum and composite. Through a combined experimental and numerical approach, this case study investigates the influence of thermophysical properties (e.g. thermal mass, conductivity and diffusivity) on the thermal response of tools.

Using analysis, the predicted effects of several geometric tooling features are demonstrated in Figure 4 [6]. These features include: 1) facesheet construction and uniformity (e.g. fillets from weld beads); 2) facesheet to substructure interfaces; and 3) localized pad-ups. Note that the facesheets for the Invar and aluminum tools in this study were constructed with large bead welds joining
multiple plates of sheet metal of nominal design thickness. This process resulted in a non-uniform facesheet thickness in corner geometries, but did not lead to significant additional thermal lag, even with the Invar tool, Figure 4 (a). This insensitivity will not always be true, as it depends on the details of the construction. Secondly, a common approach for substructure attachment, to ensure minimal fit-up gaps, is to apply intermittent joints via welding in metallic tools or tabbing processes in the case of composite tools. This interface plays a critical role in the structural integrity of the tool but is also seen to play a critical role in the heating characteristics of the tool, as shown in Figure 4 (b) (as also later shown in Figure 6 using IR thermography). This effect is most apparent in the Invar and composite tools where a noticeable local thermal lag is observed. Note that the model underestimates the effect of the substructure attachment effects likely because the model does not include the actual thermal resistance of the joint surfaces. Finally, for composite tools, pad-up geometries are often used to ensure a minimum laminate thickness to maintain vacuum integrity in blind holes. From Figure 4 (c), it is observed that there is a significant thermal lag at these facesheet edge features that is not evident in either the Invar and aluminum tools.

Characterization Methods
Various experimental and numerical methods are available to study the thermal response of the tools and equipment. Experimental methods include airflow visualization using tufts, velocity qualification using anemometers, measuring HTCs using lumped mass calorimetry and measuring surface temperatures with TCs or infrared (IR) thermography [6–10]. For simulation purposes, characterization of the boundary conditions of a thermal simulation have typically relied upon lumped thermal masses, or calorimeters, to assess the HTCs applied across the surfaces of parts. This methodology is now generally accepted as the standard for modern heat transfer simulation for composites manufacturing (e.g. [6–9]). New methods are continually being explored. For example, techniques such as IR thermography [10] and CFD [11] allow for an intuitive three-dimensional interpretation of complex heat transfer phenomena. Experimental methods are also increasingly becoming available for the robust characterization of the material properties used in the thermal modelling of cure processes. Lab-scale methods using differential scanning calorimetry (DSC) and slab conduction studies are two such methods (e.g. [9], [12]). Thermal analysis tools range from closed-form analytical expressions to numerical manufacturing simulation software, such as the commercially available COMPRO and RAVEN packages (e.g. [13], [14]).

Thermal Tool Survey
A combined experimental and numerical approach is used to study the effects of tooling decisions at global and local scales. For this purpose, thermal surveys of three small-scale tools with nominally identical geometries fabricated from typical tooling materials: Invar 36 (Invar), aluminum 6061-T6 (aluminum) and CFRP (composite) are compared. Using a combination of TCs and IR thermography, an investigation of the tool surface temperature distribution during a heat up cycle is conducted. Thermal simulation is then used and validated to further study the relationship between heating rates and surface temperature uniformity.

The overall dimensions of these tools, shown in Figure 5, are about 1.2 m × 0.8 m × 0.48 m with a 12.7 mm nominal facesheet thickness. Thermophysical properties of these tools are summarized in Table 1. For each tool, seven TCs were used to monitor the surface temperature during a heat cycle of 5°C/min from room temperature to 100°C. The tools were heated convectively at atmospheric pressure of about 101 kPa in the autoclave which was discussed
Thermal analysis tools (DSC) and slab conduction studies are two such methods using differential scanning calorimetry characterization of the material properties used in also increasingly becoming available for the robust transfer phenomena. Experimental methods are three-dimensional interpretation of complex heat mography [10] and CFD [11] allow for an intuitive exploited. For example, techniques such as IR thermation using anemometers, measuring HTCs using airflow visualization using tufts, velocity qualifi ca-

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Characterization Methods

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The surfaces of parts. This methodology is now available to study the thermal response of the tools characteristics that is not evident in either the Invar and aluminum tools.

Thermophysical properties of typical tooling materials [13].

<table>
<thead>
<tr>
<th>Material</th>
<th>ρ (kg/m³)</th>
<th>C_p (J/kg K)</th>
<th>k (W/(m K))</th>
<th>a_s (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INVAR</td>
<td>8000</td>
<td>515</td>
<td>11.0</td>
<td>2.67 × 10⁻⁶</td>
</tr>
<tr>
<td>ALUMINUM</td>
<td>2710</td>
<td>896</td>
<td>167</td>
<td>68.9 × 10⁻⁶</td>
</tr>
<tr>
<td>COMPOSITE</td>
<td>1580</td>
<td>870</td>
<td>0.69</td>
<td>0.50 × 10⁻⁶</td>
</tr>
</tbody>
</table>

FIGURE 5. Three tools with nominally similar geometries (1.2m×0.8 m×0.48 m) fabricated from typical tooling materials: (a) Invar 36, (b) Aluminum 6061-T6 and (c) Composite CFRP.

(a) Invar tool (b) Aluminum tool (c) Composite tool
earlier in Figure 2. IR images of the respective tool surfaces taken at the end of the cycle are shown in Figure 6. The details of the IR thermography method used in this study are explained in recent works by the authors [6, 10].

From the experimental data in Figure 6, it is observed that maximum tool surface temperature for the Invar tool is 59° C, for the aluminum tool it is 68° C, and lastly for the composite tool it is 78° C. The range of measured thermal lags with respect to the autoclave temperature was about 41–60° C for the Invar tool, 32–45° C for the aluminum tool and 22–49° C for the composite tool. These results highlight the wide temperature distribution experienced across the tool surface, and also shows that the Invar tool is the least thermally responsive while the composite tool is the most thermally responsive. On the other hand, the aluminum tool shows the lowest in-plane thermal gradient of 13° C while the composite tool shows the highest in-plane thermal gradient of 27° C across the tool surface. Substructure effects, creating localized cold zones on the Invar and composite tools surfaces are visible while this effect is not observed on the aluminum tool surface.

ABAQUS heat transfer simulations were performed using predicted CFD HTC boundaries, as described earlier in this paper. These results are presented in Figure 6, and show that: 1) the combined simulation is capable of reasonably recreating the IR thermography experimental measurements; and thus 2) the numerical approach can be used to further investigate other global and local tooling features.

**Part Thermal Profile**

Ultimately, composites manufacturers are most concerned with the thermal management of parts during processing. In this second case study, results obtained from experimental thermal profiles of 3.1 mm thick (16 ply) T800H/3900-2 C-shaped parts cured on the same family of small-scale Invar, aluminum and composite tools are discussed [15].

These C-shaped parts were cured using a nominal 180 °C single-hold cure cycle. In each autoclave run, parts and tools were purposefully located in the same orientation and comparable location forward/aft in the autoclave to reduce the variation in autoclave heat transfer (Figure 7 (a)). Prior work has shown that this particular autoclave, the same autoclave as discussed earlier in this paper, exhibits poor airflow uniformity [9]. Modulation of the autoclave air temperature is caused by the autoclave controller. Parts and tools were extensively instrumented with TCs. A comparative thermal analysis of parts cured at the centre of the male section of the three respective tools is performed using experimental data from: 1) a part TC located along the edge of the part at the web centre part/bag interface (surface); and 2) a corresponding insulated tool TC on the underside tool surface (underside) (Figure 7 (b)).

The experimentally measured results are shown as both temperature profile, and temperature difference with respect to the autoclave air temperature, plots in Figure 8. Temperature profile plots are commonly used to visualize thermal profiling results. However, following on from work by Rasekh et al [13], we introduce a complementary temperature difference plot to determine when parts and tools reach a transient steady state condition during cure. Thermal lag is denoted as a negative value. A positive value, or thermal overshoot, is permissible only in the event of an exotherm.
During the heat up, the experimental data shows a consistent correlation between thermal lag and overall tool thermal mass (Table 1). Based on the underside tool surface temperature, the Invar tool is the least thermally responsive since the thermal lag with respect to the autoclave air temperature is about 14 °C (Figure 8 (a)) compared to the aluminum and composite tools, with respective thermal lags of 8.0 °C (Figure 8 (b)) and 6.4 °C (Figure 8 (c)). Further insight during the heat up segment of the cure cycle requires careful interpretation of the temperature difference plots. The Invar tool (Figure 8 (a)) thermal lag is not affected by pressure application at about t = 30 min, whereas the aluminum and composite tools (Figure 8 (b) and (c)) show a perturbation at this stage. A currently unexplained effect is that the part leads the tool for the Invar tool, is the same temperature for the composite tool, and lags the tool for the aluminum tool. One hypothesis, yet to be verified, is that this is the result of curing small parts on much larger tools. Tool size effects have previously been reported in work by Shimizu et al [16]. In general, it is important to evaluate the validity of an undersized charge on a large tool: the results cannot be directly applied to a larger part on the same tool. Finally, all the tools show a zero-temperature difference on the hold, as would be expected, within the limits of the accuracy of thermocouples, typically of the order of ± 1.5 °C.

Discussion and Summary

The work presented and discussed in this paper illustrates the importance of factoring thermal management strategies into tooling design for composites processing. It was shown that the combined use of experimental tests and numerical simulation can provide useful insights relating to how tooling decisions influence the thermal response of tools and parts. These decisions can affect the global and local response of the Equipment–Tool–Part–Material (ETPM) manufacturing system. The global scale effects discussed included tool-equipment interaction, tooling geometry and substructure configuration and nesting/loading scenarios. The local scale effects discussed included geometric tooling features, such as material selection, facesheet construction and uniformity, and localized pad-ups. Based on an awareness of these effects, thermal performance can be included in tool design practices in addition
to considerations of mechanical performance and durability.

Two case studies were presented. The first study was a thermal tool survey using infrared (IR) thermography to investigate thermal variation across the tool surfaces of a family of identical tools fabricated from Invar 36 (Invar), aluminum (Al-alloy 6061-T6) and composite (CFRP). Thermal lags and temperature distributions were shown to be affected by tooling materials and geometric tooling features. Simulations demonstrated that the experimentally observed results can be appropriately recreated with reasonable accuracy for design study purposes. The second study examined experimental thermal profile data for C-shaped parts cured on these tools to investigate the effect tooling decisions have on the thermal management of curing laminates. It was shown that for thin parts, the thermal response is dominated by the tool. The trends in the experimental thermal profile data can be explained in terms of the thermophysical properties and overall thermal mass of the tool, as well as the relative size of the part.

In summary, the basis for a science based composites manufacturing practice and the use of manufacturing simulation as a job-aid was highlighted. While the focus of this paper was to introduce the effect of tooling decisions on thermal management outcomes in composites processing, ongoing and future work that formalizes science based composites manufacturing practice is underway (e.g. [3, 11, 17–19]).

Acknowledgements

The authors would like to thank the Canadian Composites Manufacturing R&D Inc. (CCMRD) Project 9.2 participants for the use of the experimental thermal profile data shown in this paper. We gratefully acknowledge Dr. Karl Nelson (The Boeing Company), Mr. Alastair McKee, Mr. Nick Cicchine and the late Corey Lynam (Convergent Manufacturing Technologies Inc.), and colleagues Dr. Goran Fernlund, Dr. Christophe Mobuchon, Dr. Casey Keulen and Mr. Gavin Tao (Composites Research Network) for their continuous technical insights and recommendations. We thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the industrial members of the Composites Research Network (The Boeing Company, Convergent Manufacturing Technologies Inc., Toray Americas, Avcorp Industries) for their financial support. Figure 2 and Figure 3 are courtesy of Dr. Christophe Mobuchon and Dr. Alireza Forghani (Composites Research Network).

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