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ADDITIVELY MANUFACTURED METAL TOOLING FOR CURE OPTIMISATION IN COMPOSITE MANUFACTURING

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Abstract: *The selection of tooling for composite manufacturing is a critical step in ensuring the quality of the resultant composite parts. The energy consumed during part manufacturing is not only used to evolve the composite properties but a substantial proportion of it is used to heat the tooling as well. Additive manufacturing (AM) offers a viable solution to reducing the tooling mass by generating complex tool architectures that can withstand the manufacturing process while offering reduced mass and additional functionalities such as cooling channels and sensor integration. A series of 16 lattice steel tools were additively manufactured and used to cure flat composite specimens. The thermal profile of the composite curing was monitored to characterise the thermal responsiveness of the tools. The curing of composites on equivalent monolithic tools of constant thickness ranging from 1- 10 mm was numerically simulated using a cure-coupled heat transfer model. The results indicate that AM tools with lattice architectures can achieve heating rates higher than 83% of the set rate while keeping the exothermic overshoot temperature below 30% of the setpoint, which its monolithic counterparts couldn't achieve. Hence lattice structures enabled by AM can push the design space into regions previously unavailable to tooling design.*

Keywords: AM tooling; Lattice structures; Thermal light weighting

1. Introduction

The composites landscape faces significant challenges presented by increasingly compressed design timescales, growing demand in productivity and the soaring complexity of products. Additionally, sustainability is a priority for the UK to achieve its pledge to reduce greenhouse gas emissions by at least 68% before 2030 and achieve net-zero by 2050 [1]. While lightweight composite structures are expected to help reduce emissions during operation, energy is the single biggest factor in the life-cycle analysis of the manufacturing process. However, how composite curing equipment and tooling are designed and manufactured has not changed since high-performance composites were first used in aerospace applications in the 1970s.

A significant step towards reducing cure cycle times is through reducing the tooling mass and improving tool architecture to enhance heat transfer. A simple estimation indicates that the tooling for composites parts is typically 10-40 times heavier than the finished part itself. Furthermore, current curing methods involve heating large volumes of air either using autoclaves or ovens. As a result of these, energy is wasted heating the environment as well as the tool during the curing cycle. Therefore, an immediate increase in thermal efficiency can be achieved via the improvement of the tool design which currently focuses on monolithic designs where there is a single block of material through-thickness of the tool. AM can be a useful route in designing complex lightweight architectures unachievable through subtractive processes such as machining. This opens up the possibility to tailor the tool design to manage the heat transfer and optimise the cure cycle while maintaining key tool characteristics such as shape accuracy and specific stiffness.

AM tooling has been trialled using various polymers, composites and metal as feedstock [2]. Among these, metal tooling would be more attractive for its durability leading to a higher number of moulding cycles, hence lower running costs. Metal Big Area Additive Manufacturing (MBAAM) system has been trialled by Oak Ridge National Laboratory using low-cost steel wire [3]. The study showcased the feasibility of producing large AM tools however the process has lower print resolution leading to considerable post-processing to improve the surface finish. On the other hand, laser powder bed fusion (L-PBF) processes, or more specifically selective laser melting (SLM), has higher resolution and opens the possibility of creating durable, bespoke, and complex designs to lightweight tools not only to withstand the manufacturing cycles but also to provide additional functionalities such as finer cooling channels and integrated sensors.

This study aims to assess the feasibility of using metal AM tools to improve composite curing in conventional ovens. This is evaluated by monitoring the temperature during experimental curing trials on AM tools and comparing it to their simulated mass-equivalent monolithic tools. This work develops a platform for characterising the thermal responsiveness of various lattice geometries and volume densities. Furthermore, this study highlights the expanded design space available for tooling designs for composite curing.

2. Materials and methods

2.1 Tool design, manufacturing, and quality characterisation

The key requirements for the tools were to be as thermally light as possible while maintaining the stiffness required for composite manufacturing. The tools were made thermally light through the choice of different lattice architectures with faceplates. Such a design helps to reduce the mass of the tool while providing sufficient stiffness for countering the stresses observed during the composite manufacturing process. Hence, a series of tools, enclosing a volume of 100 mm × 100 mm × 10 mm, were manufactured using the SLM process at the University of Bath to manufacture flat composite laminates of 45 mm × 45 mm. Lattices were designed using Gen3D Sulis Lattice software (Sulis V1.9.10, Gen3D, Bath, UK) [4]. The lattice geometries selected to test were planar diamond, a diamond with cut-outs, gyroid and graded gyroid. The tools were built using a RenishawAM250 SLM machine using 316L Stainless Steel (SS316L) powder in an inert argon atmosphere. A total of 16 tools were manufactured on a single build plate as shown in Figure 1. As this study is focused on the preliminary evaluation of the as-built metal tools, no post-build treatments of the tools were done to either improve the surface finish or strength properties.

A planar diamond lattice was the simplest geometry that was selected that provides strength, however, it may not allow for the same airflow through the lattice volume as the gyroid lattices. The diamond geometry was selected as a honeycomb-style geometry whose 45° angle ensures it can be manufactured by SLM without any need for support structures and no constraints in terms of the cell size. On the other hand, a diamond with cut-outs was used to improve the convective flow through architecture which, in a simple planar diamond lattice would be restricted due to the partially enclosed unit cells.

A gyroid is a specific type of triply periodic minimal surface (TPMS) as it contains no joints or discontinuities throughout its volume. TPMS lattices are advantageous in maximising surface area for a given volume, a key characteristic required for heat exchangers [5]. Such lattices are manufacturable due to the availability of additive processes and challenging via subtractive processes. Another architecture selected was a variation of the gyroid architecture were the volume density progressively increases closer to the faceplate. This design would promote conductive heat transfer closer to the part surface which is crucial for control of exothermic reactions in the composite part while optimising the tool mass.

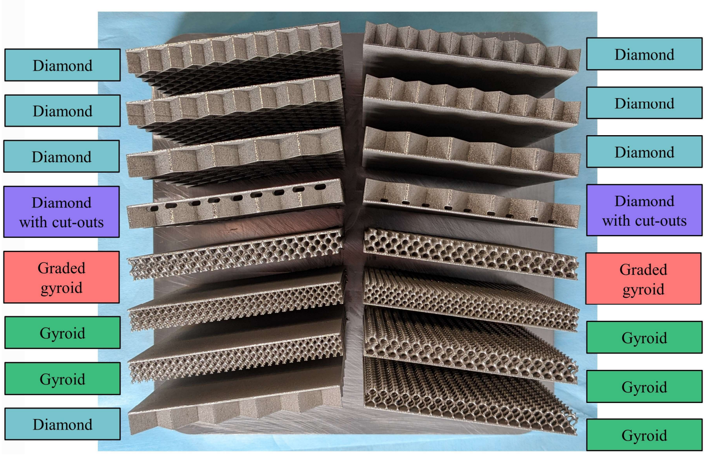

Figure 1 AM tools of varying configurations on the build plate

2.2 Composite materials and manufacturing

The composite was prepared using 14 plies of 40 mm x 40 mm prepreg (SHD) comprised of MTC400 Epoxy resin as the matrix and 415 gsm twill weave fabric made of T700 carbon fibre as the reinforcement. The as-built faceplate surface was used to manufacture the composite sample and the bagging scheme is illustrated in Figure 2 (a). A thermocouple was placed in the centre of the prepreg stack to capture the thermal history through the cure cycle. The first series of 8 tools were connected using Teflon tubes to reduce the number of oven cycles required to experiment, as shown in Figure 2 (b).

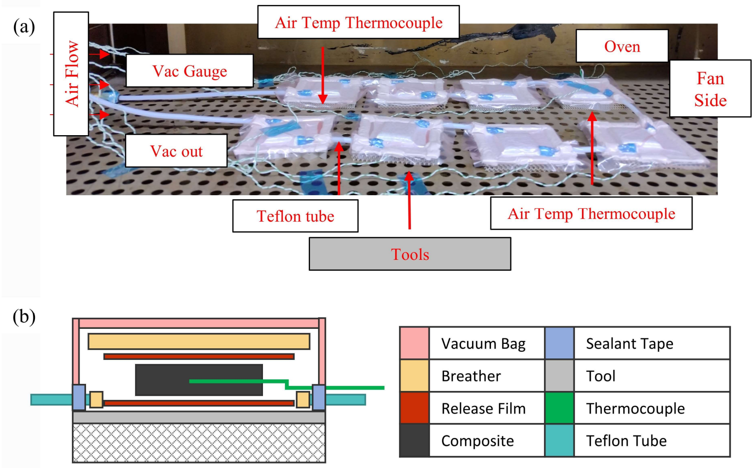

Figure 2 Bagging and curing scheme for the AM tools.

To understand any effect arising from the location of the tool in the oven, two additional thermocouples were placed at the extreme ends of the series of tools to capture the air temperature. The vacuum in this series was ensured to be 29 inHg in both of the runs. The prepared tools were then placed in a conventional oven (Carbolite) for curing. The thermocouples were connected to a datalogger (Pico Logger), and temperature data were collected at a sampling rate of 1 Hz. The cure schedule was, to ramp up from room temperature at a heating rate of 3°C/min to reach 135°C, dwell for 1 hour, and followed by a cool down at 2°C /min to reach 30°C.

2.3 Numerical model and cure simulation

The numerical model used to run the cure simulations for monolithic tools was set up using a cure-kinetics coupled transient heat transfer analysis in ABAQUS. The composite thickness was 6.2 mm based on the average thickness measured from the experimental trial and was modelled with homogenised properties. A monolithic tool of 100 mm in width was used with four different thicknesses: 1 mm, 2 mm, 5 mm, and 10 mm. The key parameters for the composite material are the specific heat capacity, and thermal conductivities (in-plane and through-thickness) which are expressed as functions of temperature, T, and Degree of Cure (DoC), α, as given in Eq. (1), and Eq. (2) and Eq. (3), respectively. The physical and thermal properties of the composite and tool are summarised in Table 1.

$$c_p(T) = 2.411 \cdot T + 1168.0 \tag{1}$$

$$\kappa_{11}(T,\alpha) = \kappa_{22}(T,\alpha) = 4.2207 + 0.0085818 \cdot T + 0.027922 \cdot \alpha \tag{2}$$

$$\kappa_{33}(T,\alpha) = 0.7344 - 0.001 \cdot T + 0.3924 \cdot \alpha - 0.0015 \cdot T \cdot \alpha \tag{3}$$

The previously developed cure-kinetic model and parameters shown in Eq (4) for the resin system were used in this work [6]. The coefficients of the cure kinetics are given in Table 2.

$$\frac{d\alpha}{dt}(T,\alpha) = \frac{\left(A_1 \cdot \exp\left(-\frac{E_1}{R \cdot T}\right) + A_2 \cdot \exp\left(-\frac{E_2}{R \cdot T}\right) \cdot \alpha^m\right) \cdot (1-\alpha)^n}{1 + \exp\left(D \cdot (\alpha + \alpha_{c0} - \alpha_{cT} \cdot T)\right)} \tag{4}$$

A target element size of 1 mm for meshing was used on the tools and the composite meshed with 6 elements through thickness. The initial time-stepping for the transient analysis was 20 s and the constraint on the maximum change in temperature at any material point of 10°C for any single time step. These parameters were chosen to sufficiently resolve the curing process time to capture the exothermic behaviour of the resin system which typically results in a rapid increase in temperature in a short time.

The outer surfaces in contact with the environment were simulated as having a convection heat transfer with a heat transfer coefficient of 20 W/(m^2.K). The sink temperature profile was then set to be the air temperature profile. The cure cycle was the same as that was applied for the experimental work on lattice structures detailed in Section 2.2.

Table 1 Thermal properties of composite material and steel

Property	Unit	Composite Material	Steel
ρ	[kg/m^3]	1586.0	7850.0
c_p	[J/(kg·K)]	Eq. (1)	500.0
κ	[W/(m·K)]	Eq. (2) and Eq. (3)	45.0

Table 2 Cure kinetic parameters for MTC 400 resin system [6].

Parameter	Units	Value
A_1	[1/s]	2.97×10^{-6}
E_1	[J/mol]	1.36×10^{-5}
A_2	[1/s]	1.28×10^{-11}
E_2	[J/mol]	9.82×10^{-4}
m	[-]	0.8473
n	[-]	2.4065
D	[-]	28.504
α_{c0}	[-]	1.326
α_{cT}	[1/K]	5.73×10^{-3}
R	[J/(mol·K)]	8.314
H	J/g	543

3. Results and discussion

All the samples, both the simulation and experimental, exhibit varying extents of exothermic reaction as observed from the overshoot in temperature above the setpoint as shown in Figure 3. There was a negligible difference in the temperature profile of 0.5°C at the two extreme ends of the series of tools, indicating the location in the oven was not a factor. Since there was a negligible difference arising from the location and the thickness of the part, the thermal response observed for various samples could be attributed to the tool itself.

These thermal profiles were used to calculate the initial heating rate, overshoot temperature and the final cooling rate observed by these samples. Both the heating and cooling rates were calculated from the linear region of the thermal profile to capture only the effects the of tool and not that of the exothermic reaction. The overshoot temperature was calculated as the increase in temperature above the oven setpoint of 135°C. The heat transfer in these cases occurs through convection at the tool surfaces followed by conductive heat transfer through the tool. The surface area exposed to the airflow is a dominant factor in the convective heat transfer while the tool mass is the primary driver in conductive heat transfer. To understand these effects, the heating rate, cooling rate and overshoot temperature are plotted against the tool mass and surface area as shown in Figure 4.

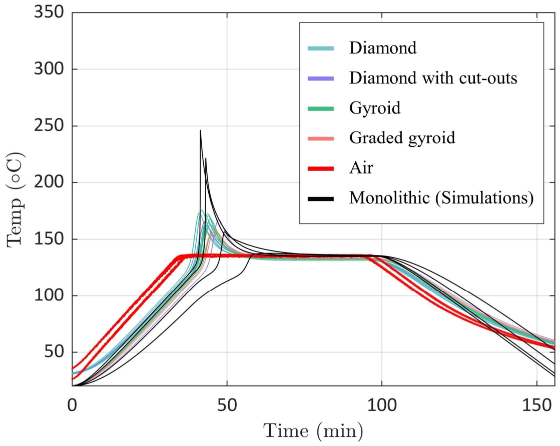

Figure 3 Thermal profile of different AM tools monitored during the experiments along with the simulated profiles for monolithic tools.

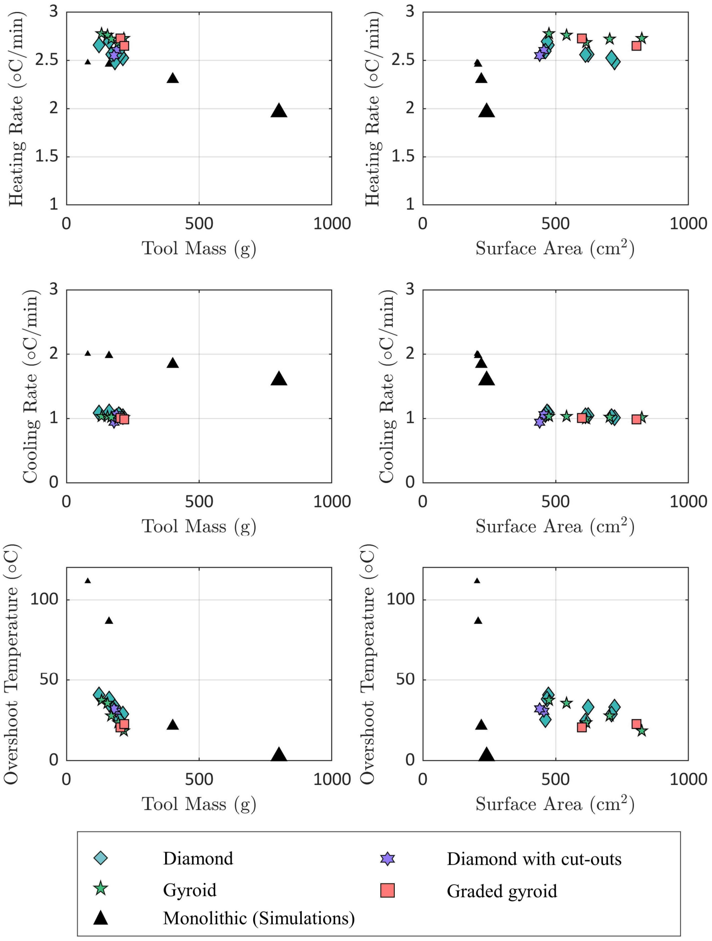

Figure 4 Heating rate, cooling rate and overshoot temperature vs. tool mass and surface area for various AM tools and the simulated monolithic tools.

All the AM tools performed better than monolithic tools with higher heating rates. The heating rates observed by the samples on monolithic tools almost linearly increase with reduced tooling mass, but no such relation could be made for AM tools given the tools had similar masses. Increasing the surface area of the tools has improved the heating indicating increased contribution from the convective heat transfer. However, the performances had minimal difference between varying AM tool configurations. On the other hand, the cooling rates were lower for the AM tools than for their monolithic counterparts. The conductive heat transfer from the cured part to the tool could potentially dominate the cooling rates. Hence, tools with a larger mass concentrated towards the faceplate would be beneficial. Hence the monolithic tool performing better could be attributed to this effect. However, further investigation is required to explore this hypothesis. The overshoot temperature is expected to increase with reduced tool mass as tools act as heat sinks in composite curing. Both, monolithic and AM tools exhibit this trend independently, however, AM tools can perform better at controlling the overshoot compared to their monolithic counterparts.

To assess the performance in cure optimisation, the tools have to be able to achieve high heating rates while controlling the exothermic temperature by conducting heat away from the part. Hence, the performance plot using these two parameters was prepared as shown in Figure 5 for the various configurations. The reduction of tool mass in monolithic mass results in high heating rates, however, results in overshoot temperatures passing well over the degradation temperature of the epoxies. But, through the use of lattice architectures an innovative design space opens up where thermal lightweight does not lead to runaway exothermic reaction.

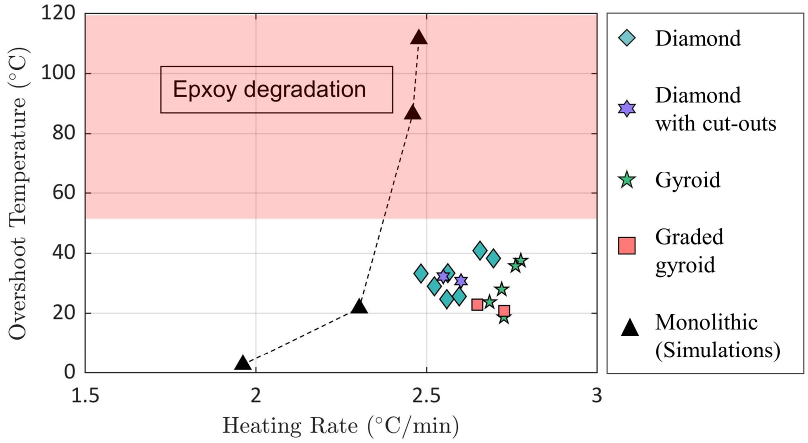

Figure 5 Design space comparison between monolithic and AM lattice tools to achieve low overshoot temperature and high heating rate.

4. Conclusion and future work

In this study, AM tools with different lattice architectures were used to cure composites and the thermal response within the composites was compared to their simulated monolithic counterparts. The key factors such as heating rate, overshoot temperature and cooling rate were used to assess the tools.

The lattice architectures enabled by AM were shown to achieve higher heating rates than their monolithic counterparts while controlling the exotherm. This was achieved by reducing the tool mass while exposing a larger surface area to convective heat transfer, thus improving the overall heat transfer. Such geometries expand the available design space for tooling leading to reduced cycle times and optimised curing. This study shows various tool designs that could be beneficial in convective curing methods. However, such lattice tools can be designed to account for other curing methods such as heated tooling to form a cyclic design methodology considering composite chemistry, curing method and tool architecture.

However, challenges remain when using AM tools, particularly in achieving surface finish without the use of additional machining as well as manufacturing larger tools using SLM. Future work would look into curing complex geometries where temperature gradients are sharper. Such a study will also have to look into including additional tooling requirements such as the surface finish, design for a layup and grading of the tooling architectures.

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5. References

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