

Exploring the discrete tools used by laminators in composites manufacturing: application of novel concept

H.V. Jones, A.P. Chatzimichali, R. Middleton, K.D. Potter & C. Ward

To cite this article: H.V. Jones, A.P. Chatzimichali, R. Middleton, K.D. Potter & C. Ward (2015) Exploring the discrete tools used by laminators in composites manufacturing: application of novel concept, *Advanced Manufacturing: Polymer & Composites Science*, 1:4, 185-198, DOI: [10.1080/20550340.2015.1105613](https://doi.org/10.1080/20550340.2015.1105613)

To link to this article: <https://doi.org/10.1080/20550340.2015.1105613>



© 2016 The Author(s). Published by Taylor & Francis



Published online: 27 Nov 2015.



Submit your article to this journal [↗](#)



Article views: 806



View Crossmark data [↗](#)

Exploring the discrete tools used by laminators in composites manufacturing: application of novel concept

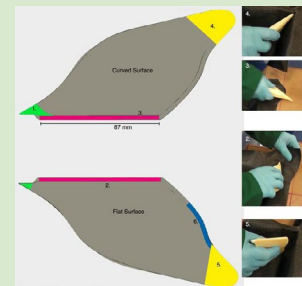
H.V. Jones*, A.P. Chatzimichali, R. Middleton, K.D. Potter and C. Ward

Advanced Composites Centre for Innovation and Science (ACCIS), University of Bristol, Queens Building, Bristol BS8 1TR, UK

Abstract This research investigates the handheld and often personally owned tools used by laminators to form advanced composites into components for aerospace, defense, and autosport; and reports on the application of a novel concept. The lack of formal knowledge that surrounds the existence and use of these tools presents an opportunity to explore what significance they have for process standardization and composites' design and manufacture. The paper presents results from layup trials that were performed to test a prototyped tool, designed with user-centered and geometry-driven research in mind. The trials showed tool use is aligned with the laminator's goals for the layup task; and suggest that it is also used as the laminator's method for reporting quality feedback. The trials also raised questions about why the laminators habitually use their tools and the necessity of supporting a laminator through the decision processes involved in a layup task. This suggests the development of a prototyped tool can be of significant benefit in the realm of skills and training.

Keywords Tools, Hand lamination, Layup trials, Composites, Manufacturing, Skills and training

Cite this article H.V. Jones, A.P. Chatzimichali, R. Middleton, K.D. Potter and C. Ward: Adv. Manuf.: Polym. Compos. Sci., 2016, 1, 185–198



Introduction

Driven by a diverse range of sectors (established and emerging), the composites industry is expected to grow^{1,2} from its value of US \$68.1 bn in 2013 to \$105.8 bn in 2020.¹ However for this growth to happen, the industry faces several challenges of supporting product design, development, and supply chains and developing skill and knowledge bases.^{1,3} Those relevant to this work are the “lack of composites skills” and the “development of the workforce with the right skills”.³ There is also the need to overcome misconceptions concerning the level of skill required to form a composite part by hand, it has been suggested in Ref. 2 that “laminators who manufacture composite parts tend to be semi-skilled workers”.² However, it is believed by the authors that the composites industry is manufacturing high-value products whilst relying on a laminator's craft skill that does not have a knowledge base and is largely dependent on their tacit knowledge. The tacit nature of a craft skill makes the knowledge more challenging to capture and exploit, but this task is necessary to challenge the perceived skill level of laminators and support the industry.

Despite the high-value sectors that drive the composites industry, the dominant manufacturing route is the craft-based process of manual forming for the vast majority of products.

*Corresponding author, email helene.jones@bristol.ac.uk

Automated processes are unable to meet geometrical and productivity requirements,^{4,5} and often require manual forming assistance to finish products. Also for smaller companies, the costs associated with automation are prohibitive.

This work is concerned with unexplored observations in the industry that could be relevant for tackling the expected growth, delivering better, faster, and cheaper composites products.⁶ The aim of the research was to explore the role played by the handheld and personally owned tools used by laminators that are ubiquitous in the industry. This is the first known attempt within research to generate a body of knowledge around these tools. Previous research has demonstrated that there is a relationship between tool use and the worker's skill level, but the focus of this study were rollers used for wet layup.⁷ An initial exploration has been conducted, and here the application of a novel concept that emerged from that work is being applied. This is to develop an understanding of how this evolving knowledge base can be implemented and exploited.

Tool use in the composites industry

Laminator's tools are used to aid forming a composites part. They are held in a laminator's hand and used to form a ply to the surface of a mold. The research has found that these tools serve three functions:

- Comfort: as layup is a manual task.
- Geometry matching: when the mold geometry that requires forming is beyond the capability of the laminator's hands.
- Additional force: for forming heavier plies.

A laminator's tool set is generally made up of number of different tools with varying geometry and material. The material tends to be what can be found or fabricated on the shop floor, either hard plastic or composite material. There is a preference for PTFE due to its low surface friction with prepreg. Their geometry is driven both by the mold's geometry and the laminator's preference. However for an identical mold geometry, laminators will all use different

shaped tools that they have fettled themselves or had done to their request, as is the practice on some shop floors. The tools have both variations in the external form for geometry matching and in the gripping features, with some having holes so they can be spun around in the hand, or others having handles that allow them to be gripped (like a hammer). These features of a tool mean the laminators develop their own techniques for layup. This suggests the tools' use is coupled to both their lack of formal recognition and the lack of a formal laminator's skill and training process. It is problematic that tool use is uncontrolled, because of their connection with process standardization and subsequent quality control.

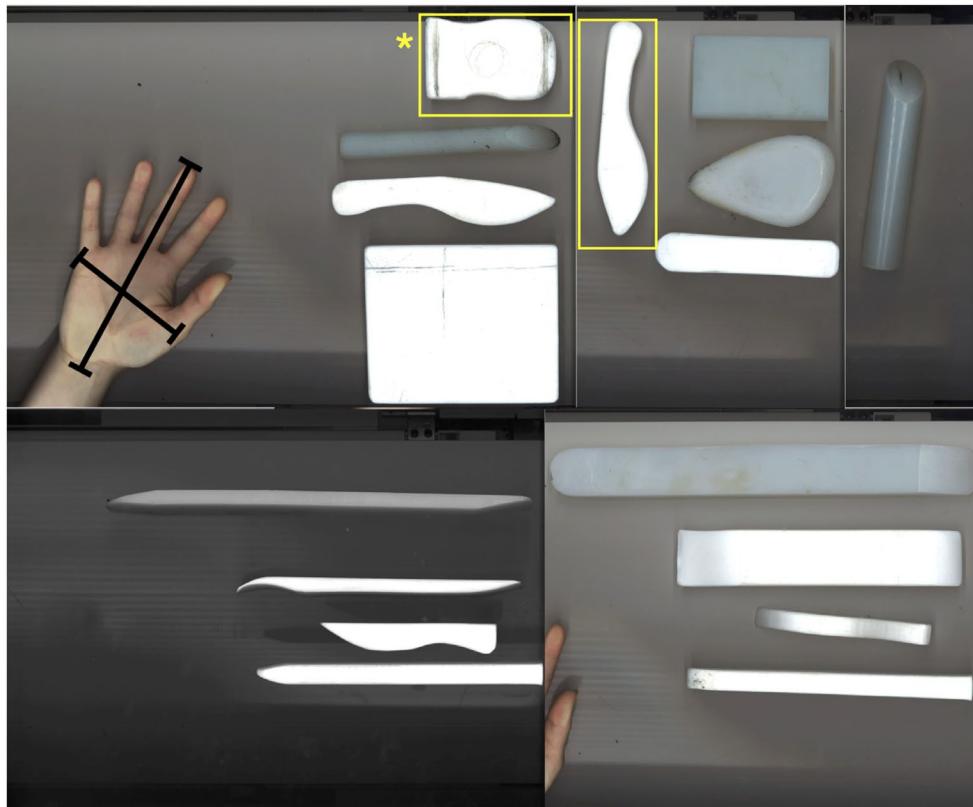


Figure 1 A complete set of “dibbers” belonging to an expert laminator, the scale of measurement is the hand of a small female adult. The width of the hand is 95 mm and the length of the hand is 165 mm



Figure 2 A set of tools belonging to a laminator. The collection shows the diversity in materials that the tools might be made out of

Figures 1 and 2 show tool sets belonging to two different laminators. The diversity of tools in each set, and between sets, reflects both the length of time the laminator has spent in the industry and the range of different mold geometries they have been required to form, and this diversity can commonly be seen in practice on a shop floor. The use of tools is ubiquitous, irrespective of simple or complex mold geometries. These tools can have different names and spelling depending on the laminator and the company, e.g. “nurkers”, “nerkers”, “dibbers”.

There are some commercially available tool sets,^{8,9} which appear almost identical to what is seen in Figs. 1 and 2. If their use is prescribed, nothing other than the laminators not having to make their own tools will change. This is because the laminator is still deciding how to use a tool and developing their individual layup technique. The development of a standardized tool is connected with skills and training, and quality control.

Tool use and the design process for composites

There is clearly an unexplored link between these dibber tools and the design process in composites. The existence of tools for the function of “geometry matching” suggests that the design process for composites extends into production, as the design of the composite product is creating another problem for the laminators to solve. The needs of laminators are not recognized by designers or manufacturing engineers, and disconnection exists in design requirements between design and manufacturing. It is believed these occur because of a lack of design for manufacture for composites.

A laminator as a craftsman is a problem solver, who develops a solution for how to approach a layup task for a particular mold geometry. This problem-solving process has been described as like a doing a “jigsaw puzzle”, with a laminator inventing their own methods, tools (including mirrors) and practices to deliver a formed ply. This further demonstrates disconnection between design and manufacture, and the lack of design for manufacture and knowledge that is required to produce manufacturing instruction sheets. The layup approach they use will change throughout the learning process for a particular job. However, this evolving approach is seen on actual products as learning is done on a job. For example, how the layup task for a first product is approached and completed will be significantly different to the subsequent and final products. This suggests that information required on manufacturing sheets is missing. Discovered techniques for layup diffuse through personal communication and “training” between laminators (experts and novices) within companies on the shop floor, and are further facilitated by the contractor nature of the industry. Laminators move between companies, and as a consequence so do their knowledge and techniques. However, this means capturing their knowledge to resolve this disconnect and develop a design for manufacture is more challenging.

For different mold geometries, a laminator uses the “same thought process to figure out how to make it”. This statement suggests a laminator employs a basic logic in three-dimensional forming, and contradicts the perception that layup is a “black art”,¹⁰ it rather implies that the logic they use has not

been articulated or investigated so it can be applied before. Initial research building a language to articulate and apply a laminator’s knowledge can be identified.^{7,10–12}

Traditionally, the tools used are made by hand and can require the most experienced laminator to be absent from the shop floor often as they produce them. This loss of expertise and hands on the shop floor is a cost and risk to the company – each tool could take up to two hours to make. The consequence means it is well worth investigating a standardized tool, for a more immediate introduction to use, as well as from a skill and training and composites design perspective. Production environments where it is believed this research could be immediately applied, are those where the workforce are recruited to meet the demands of specific mold geometries and production rates.

Experimental approach

A prototype of a tool (Fig. 3) was fabricated in PEEK using SLS Additive Manufacturing. The intention was to develop a concept for a standardized tool, so the prototype is formed of different landscapes rather than quantified features. In Fig. 3a, eight different geometrical features have been coded on the schematic of the tool. The bright green, bright blue, pink, and yellow features are for forming plies. Each feature is for forming plies to a particular type of mold geometry, and the use of these features is achieved by gripping the tool in a particular fashion. The purple feature is to support the hand during the forming, providing a continuous load line through the tool, hand, and arm. The peach feature is for both grip and moving the tool around in your hand so that different forming features (particularly the bright green and yellow) can be used with ease. The dark green and dark blue features are for sequencing individual forming gestures; forming gestures are using a feature on the tool to form a ply. Sequencing is when the mold geometry requires a different feature on the tool to be used and a subtle change in grip is required (moving from the pink to bright green feature), and these features support these transitions in forming features in the layup.

Whilst the features of this tool were designed for mold geometries commonly seen in aerospace components, it can be used more generically to prove a concept of a standardized tool (rather than the current handmade tools) that could be supportive to the composites industry. Consequently, the design of a tool for the rail industry could well be different as the design of the tool was geometry driven. This would lead to the design of a handheld tool becoming an integral part of a composites design for manufacture, and coupled to the design of a mold from its inception. Additionally, using the concept of the standardized tool, a production route dependent on craftsmanship can be explored as an industrially set up standardized process.

The weight of the tool obviously depends on the material that was used to make it, and further testing is required to validate the durability and robustness of the tool. This prototype required no surface finishing, but was fettled by a laminator, after one trial. This was to soften the point on the bright green forming feature. This was considered acceptable as a laminator might choose to soften the edges of a standardized tool due to how it was manufactured. It is not thought that fettling of

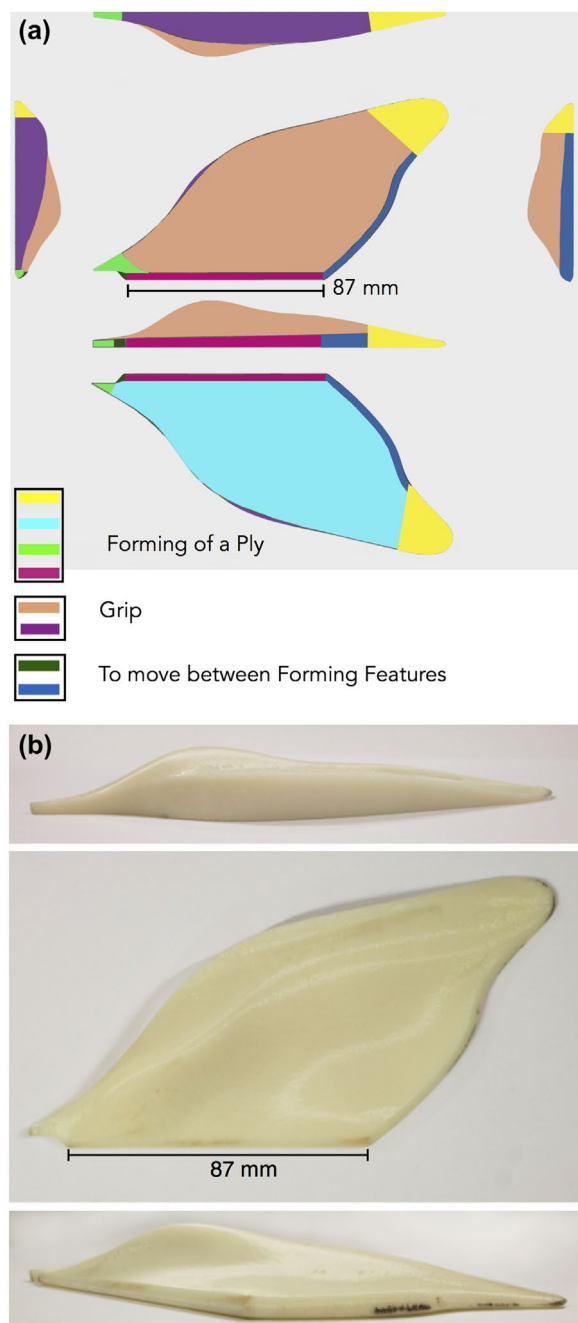


Figure 3 a CAD drawings of the prototyped tool, from all six views. The eight different geometrical features on the tool have all been coded in a different color, see legend; and b Photographs of the prototyped tool (this was fabricated in PEEK using SLS AM). Further examples have been manufactured from ABS using injection molding. The Dibber is a registered design (UK Reg. Design 4037188)

this nature is detrimental to the intention of standardizing the tools, as the overall landscape of features is not being changed.

User feedback

Laminators provided initial anecdotal feedback on the prototype, with a focus on the geometrical features and how it felt in their hands. The laminators did not trial the prototype for a layup task. They worked on the shop floor of a composites

manufacturer producing a range of composite products, including components for aerospace and rail industries, which requires the flexibility of an agile production facility. Due to the wide variety in components that are made here, the practice of making tools for specific jobs could be seen. For example, the geometries of some molds required that the tools were made using sharp metal spatulas with composite grips.

The laminators providing feedback were both contractors and employees with a range of experience, from trainee to 14 years. Each had their own personally owned tool set and geometrical variation could be seen between their sets, even for identical mold geometries.

Layup trials

An expert laminator with over 20 years experience was used to trial the prototyped tool for a layup task. The laminator's own dibbers were also used as a control for this activity. The layup task was the forming of one ply (at a time) of a woven reinforcement to a mold, as seen in Fig. 4a. The task was chosen because of the geometrical complexity of the mold and the subsequent challenges in manipulating the plies. Molds used for previous investigations into hand lamination^{10,11} also informed its choice. The geometrical features on the mold are representative of geometries seen in composites products for the aerospace and transport sectors that are formed using hand layup, and was made from tooling board (high-density [580 kg/m³] polyurethane).

The only manufacturing guidance given was the starting point, and this has been highlighted with an asterisk in Fig. 4a. However, the quality of the formed ply was paramount. The laminator to form their quality acceptance criteria, as seen in practice, used the esthetics of the formed ply. Judgments were taken on the placement of the ply to the edge of the mold (denoted by the red line in Fig. 4a) and signs of defects (bubbles, wrinkles, bridges etc.) in the formed ply. Any comments or feedback that the laminator made about their satisfaction with a particular layup task was manually recorded. The layup tasks were also recorded using a high-definition video camera (Panasonic HC-V500) and observations were manually recorded. The video camera was set up at the angle to the mold captured in Fig. 4. This is because the dominant quadrant of the mold being worked by the laminator was in the forefront of the video image, without being blocked by where the laminator was standing. This positioning allowed for use of the prototype to be captured in detail. These details of how the prototype was used in the trials include how it was grasped to use different forming features, how it was used to form different features on the mold, how many times it was used on a particular feature of mold, and also recorded timings for each layup trial. These videos were then analyzed to extract data relating to these details and the region of the mold geometry the laminator was working on could be seen. The observations and comments were correlated with this extracted data. This was done so data about how the laminator approached the layup task for each trial could be extracted. A map was produced for each layup trial that detailed how the prototype was used in relation to the mold geometry over time. All the trials were performed in a clean room to industry standard conditions (temp, humidity).

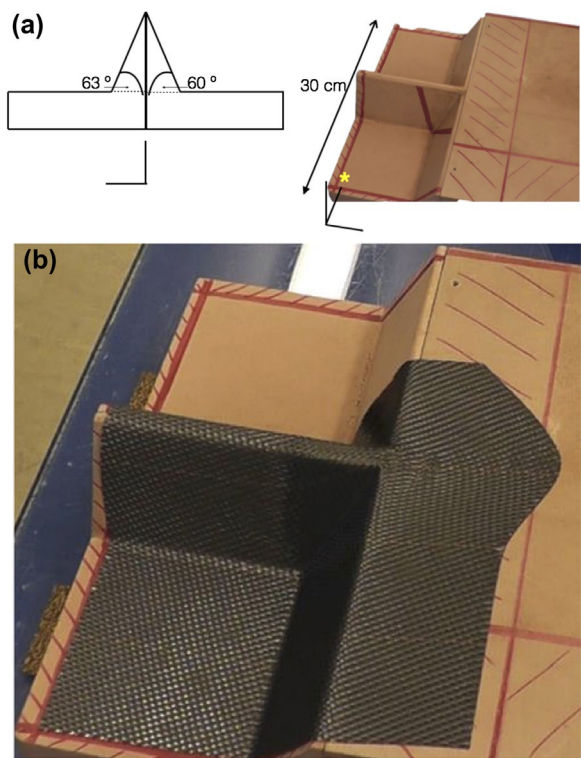


Figure 4 a A photograph and schematic of the mold used for the layup trials, and b a photograph of a formed ply on the mold

An initial ply was formed to the mold but not included in the trials outputs, to allow the laminator to become familiar with the working environment and to determine a forming route for a ply on this mold geometry. An example of a formed ply on the mold can be seen in Fig. 4b.

Six trials of the layup task were completed. For each, the tools used have been summarized in Table 1, and a single category of tool was used for each trial. For Trials 1 and 4, the laminator selected and used their own tools (Fig. 1), and their choice was driven by the geometry of the mold. In these two layup tasks, the laminator swapped which tool they used as needed. For all other trials, the prototyped tool was used. Between Trials 2 and 3, the tip of prototype (as highlighted in bright green on Fig. 3) was sanded to take the edge off the point. A hairdryer was also used on all the trials to aid the layup process, by making the ply easier to form. This is commonly seen in practice, so it was permitted.

As noted, in all of the trials the goal for the layup task was completion to the highest possible quality, but this was risked for Trial 4 where the laminator changed their goal to completion of the task in the fastest possible time. As done previously, time was used as a standard variable to measure the effort between layup tasks.^{10,13} It was chosen because in principle it allows learning curves and costs¹⁴ associated with the prototypes use to be derived. However, there is also a lack of clarity around what a measured layup defect in composites

is,⁴ this means using quality as a variable beyond the anecdotal is challenging. Thus, for these lamination tasks, the laminator used their own judgment to determine when they were satisfied with the quality, and hence completion of the task. Again this is commonly seen in practice, although evidence for this is difficult.

From previous research, it is evident that the material used for lamination impacts on the proportion of the task that is completed by manual manipulation or tool forming.¹⁰ The tack and weight of the material are two particularly important characteristics because if the material does not stick to the mold the main forming process will be manual manipulation, rather than with a tool. The material chosen was selected using guidance from a laminator. The material details were TM49-3B 2 × 2 Twill Carbon prepreg manufactured by ACG.¹⁵ The plies used were 30-cm squares in a 0/90° configuration.

Demonstration

After Trial 6, the laminator demonstrated how they felt the features on the tool and mold geometry were coupled, or not. These were recorded using the same setup as in Section Layup trials.

Results

In this section, the results from the user feedback and layup trials are presented.

User feedback

Initial comments provided by laminators on a shop floor were largely positive, and have importance for developing the design of the prototype. From this development perspective, particular points were:

- Observations that the tool design meant the grip and the gesture for the tool's use had been coupled together.
- Mirroring of the curved surface feature.

The motivations for mirroring the curved surface feature were so the tool could be rotated and moved around in the hand, and consequently held both ways round and consequently be used by both right- and left-handed laminators. However, the need to have a flat surface for smoothing incorporated on to the tool suggested making a mirror image tool for left-handed laminators could be more appropriate.

- Making two different scale tools.

So the same shaped tool can be used for smaller molds and larger molds.

- Incorporating a thin compliant feature.

This would be used instead of the hand for final consolidation of the material to a mold.

In summary, for prototype development, these comments will be combined with the results from how the tool is used in practice. For example, if it is found the flat surface on the prototype is not used, mirroring the curved surface could be pursued as a solution that is both suitable from a design and manufacturing perspective.

Table 1 A summary of the trial number and the tool that was used

Trial number	1	2	3	4	5	6
Tool used	Laminator's own	Prototype	Sanded prototype	Laminator's own	Sanded prototype	Sanded prototype

Layup trials

Times

The layup time in Trial 1 was taken to be the standard and the times for the subsequent layup trials have been normalized to it (Fig. 5). The different symbols denote the tools that the laminator used, either their own or the prototype.

The length of time taken to complete a layup task was taken from when the laminator positioned the ply at the datum to when their hands left the surface of the formed ply. Pauses and breaks to pick up tools are included in this time; however, from the recorded video it is possible to get details of these and deduce the percentage of the layup task that consisted of active and inactive forming. From these recorded videos, any particular behaviors (e.g. which tool they were using, how they used the tool) that resulted in changes to the layup time could be seen.

The laminator's task was to achieve a quality of layup that they would perform in practice and their satisfaction with the completion of the task was noted however this was not graded. After the completion of the first task, it was noted the laminator was "happy with [the] layup", and thus achieving this standard became the benchmark for subsequent trials.

Forming processes

In each trial, the layup task was a series of three forming activities involving either just the laminator manually manipulating the ply to form it, using the tool to form it, or pausing to pick up and put down the tools. Figure 6 shows how each trial broke down into these three different forming activities. Again Trial 1 was taken as the standard time, therefore the cumulative normalized time for each trial is equal to the normalized time displayed in Fig. 5. As the trials progressed, a reduction in the extent of time a tool spent in the laminator's hand can be seen, as the overall time to complete the task also reduces.

Table 2 also displays the percentage of the layup time for each task the laminator spent on a particular activity. It is included to highlight how the laminator changed their behavior for the layup in Trial 4 when their goal changed to completion of the task in the fastest time. Despite this Trial 6 showed that it was possible to complete the task in a quicker time, in this trial the prototype was used.

For all the trials, the percentage of the layup task that was spent inactive (pausing or picking up tools) was consistent (av. 9%). However, to achieve their objective of completing the task in the fastest possible time in Trial 4 the laminator near halved their use of tools to form a ply in Trial 4 (22%) compared to all the other trials (av. 40%). In all the trials, except Trial 4, the percentage of layup time spent on manual manipulation was also consistent (av. 51%), in Trial 4 this increased in 67%.

Mold geometry and tool use

Figure 7 represents how the mold geometry was broken down into different regions so the data from the video analysis of the trials can be represented. Edges are numbered in red, and the line (11) has also been shown in red. The flat regions have been numbered in black, and concave features (4, 14) where the ramped surfaces meet have been labeled in blue. Note that 4 is intersected by feature 5 and is represented by a gray region.

Each trial was analyzed from the videos so each time a tool was used the regions of the mold that were being worked were extracted. This data has been displayed in Fig. 8 where each row represents a trial, and each mold schematic represents the use of a tool to form a ply. On the schematic, the regions where the tool was used have been highlighted, as surfaces (blue) and edges (red). The highlighted regions may have been worked more than once during each tool forming action, but this is not represented in Fig. 8, as the aim was to explore how the tool had been used in relation to the regions that had been worked.

There does not appear to be any obvious trend within Fig. 8, other than that the number of times a tool is used does not correlate with the amount of time it is used to form a ply (Fig. 6). Trial 4 particularly highlights this, where the tool was used on the highest number of separate occasions but the percentage of forming done using a tool was the lowest (Table 2).

Coupling the prototyped tool's features with mold features

During the trials, it was observed that the laminator was seemingly coupling features on the prototyped tool with the regions of the mold they were forming. The video analysis suggested that there were six regions on the tool that the laminator had regularly used. These six regions on both surfaces of the tool face have been highlighted in Fig. 9. It is worth noting that if a surface of a tool is used on an opposite face (e.g. face 2 and 3 identified in Fig. 9) they have been considered as a different feature because the laminator had to grip the tool differently to use them. Picture examples of the prototype in use have also been included in Fig. 9 to clarify this point.

After Trial 6, the laminator was able to articulate how the prototyped tool could be coupled with features on the mold geometry (Fig. 10). Each row in Fig. 10 represents how the tool is coupled to a particular feature on the mold and this has been called an action. In Fig. 10, the region of the tool that is coupled has been highlighted in black and the region of the mold has been highlighted with a red line or a blue region. Some of the actions have more than one stage and the schematics should be read sequentially across the row. For some actions more than one feature on the tool is used. For an action, the direction of movement for the tool is shown with a green arrow.

Figure 11 presents how the features on the tool and mold were coupled during the layup task in Trial 6. Trial 6 was selected as the laminator has had the most experience of using the prototype. Again the region of the tool being used has been highlighted in black and the region of the mold being formed with a red line or a blue region. Analyzing the video in this way was done to compare how the prototype was used with what was suggested in Fig. 10. This analysis was also done to develop both the prototype's instructions for use and its design.

To explain Fig. 11 for each mold feature, all the different tool couplings that were seen have been shown in a column. For a particular mold feature, the columns have been arranged to show the frequency that a particular tool feature was used for. At the top of the column is the most commonly used feature on the tool and at the bottom the least commonly used. From

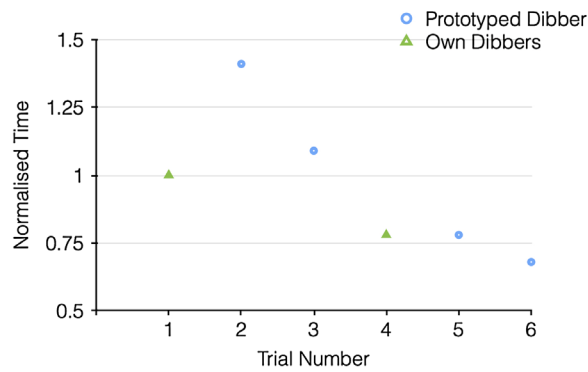


Figure 5 Normalized times for the trials. Trial 1 taken as the standard time

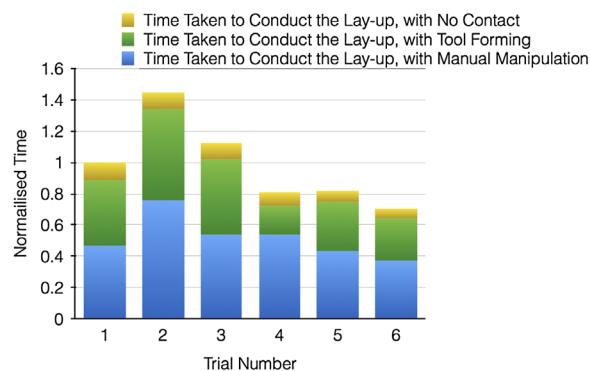


Figure 6 Normalized times for how the trials divide down into three different forming techniques: manipulation, tool forming or no contact. Again Trial 1 taken as the standard time

a training perspective, it is important to identify which feature of the tool was most commonly used for a specific geometry, as it suggests how the tool was used with most ease.

Using these results, grips to use the tool for specific mold features can be suggested, and provide a route for integrating a tool into skills and training and design for manufacture.

Discussion

Here the results that were presented in Section Results will be discussed.

Learning curves

On the graph in Fig. 5, a clear learning curve with no plateau for the layup trials can be seen. Learning for both the prototyped tool and the mold geometry would be expected, as the laminator is not familiar with either for this particular layup task. It is natural to expect that the order of the trials has impacted the learning curve, as changing between using their own tools and the prototype will disrupt their learning, and requires aspects of relearning and forgetting.^{16,17} The

normalized time in Trials 2 and 3 has increased from Trial 1, and this is because the laminator was learning how to use the prototyped tool rather their own. Naturally, this caused the layup task to take longer. The decrease in the time between Trials 2 and 3 could either be attributed to the learning curve or the fact that the laminator fettled the prototype between these trials. This fettling then allowed the laminator to sequence the gestures for forming different areas of the mold. The normalized time in Trial 4 has reduced from Trial 1; on both these trials the laminator used their own tools. This reduction in time can therefore be attributed to the learning curve for the mold geometry, although it could also be associated with the laminators motivation to complete the layup task in the fastest possible time. Trials 3 and 6 are comparable in their position in the series and the normalized time for Trial 6 (0.68) has nearly halved in comparison to Trial 3 (1.09).

Currently, as a laminator's tools are personal when a laminator changes their tool, there is no mechanism to connect this individual learning with an organization's learning. However, the use of the prototype as a standardized tool in a training and production environment provides organizations with a method to connect individual and company learning. The incorporation of a standardized tool as an integral part of design for manufacture allows the costs associated with different designs from disrupting a laminator's learning to be considered from an early stage.

Analysis of the videos suggests that for each trial the order of forming the ply over the mold was unique; however, general trends in the forming route could be identified. The route will be discussed further in Section Mold geometry and tool use, but here it is important to note that there is a general approach to the layup task. This suggests a significant proportion of the learning seen can be attributed to the handling of the prototype rather than refining the forming route for this mold geometry.

Forming processes

Figure 6 shows that in all the layup trials the laminator spent most of their time forming the prepreg using their hands. Trial 2 is the first layup trial that the laminator performed with the prototyped tool and the normalized time for forming the prepreg with both a tool and their hands has increased. As the time spent on manual manipulation has also increased, it suggests using a different tool requires the laminator to relearn how to layup, and develop their technique. Compared to the other trials, Trial 4 shows a significantly larger difference in the time spent on manual and tool forming. This point will be explored further using the representation of the data in Table 2.

Table 2 shows that for all of the trials except Trial 4 there is around a 10% difference in the percentage of time spent on manual manipulation and tool forming. These results show

Table 2 The percentage that each forming method was used in each trial

Trial number	1	2	3	4	5	6
Percentage of time taken to conduct the layup, with manual manipulation	49.5	52	48	67	53	52
Percentage of time taken to conduct the layup, with tool forming	40.5	40	43	22	39	39
Percentage of time taken to conduct the layup, with no contact	10	8	9	11	8	9

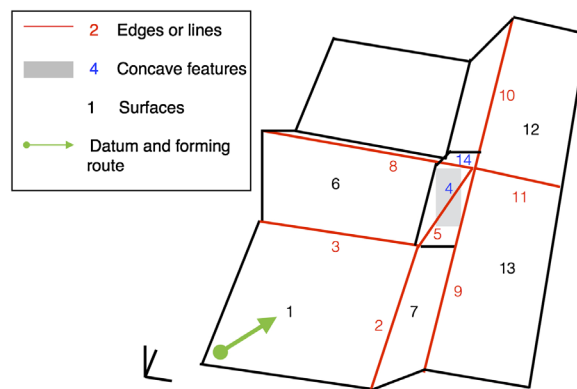


Figure 7 A schematic of the mold divided into different geometrical features for the analysis of how the tool was used in the layup task. It also shows the forming route. Red lines and numbers denote edges or lines, black numbers denote flat surfaces and blue numbers and gray regions denote concave features where two surfaces meet

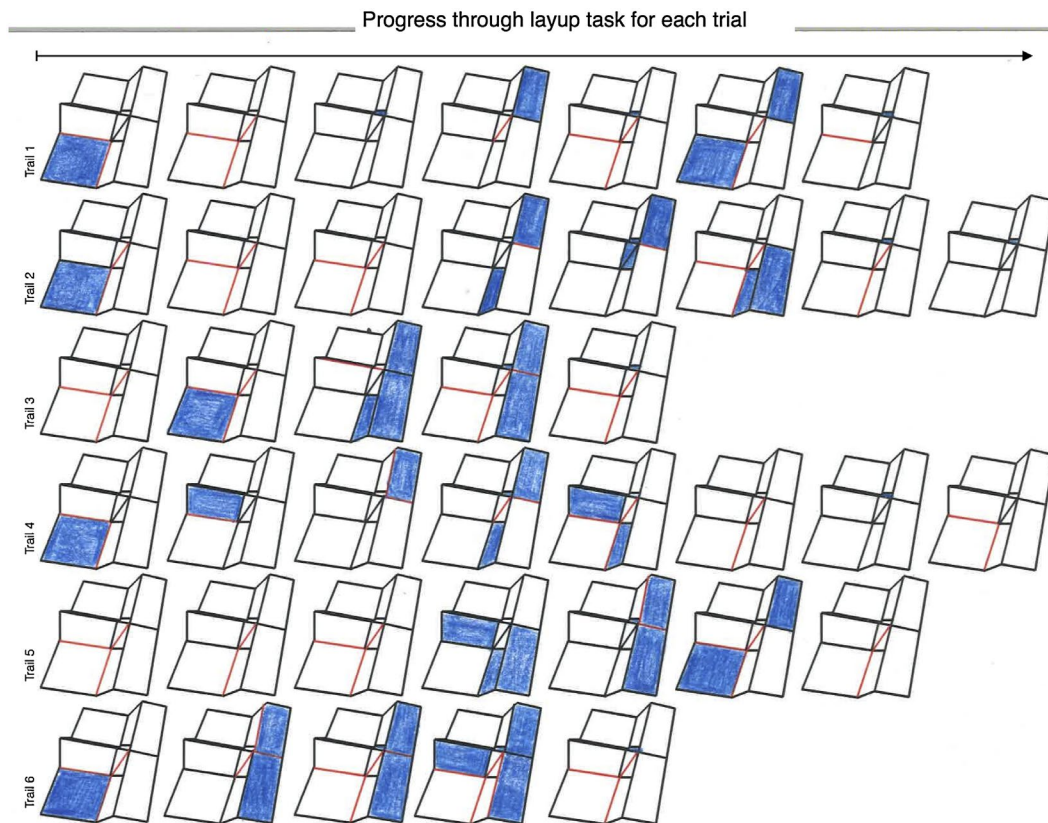


Figure 8 Schematic of the tool use on different features of the mold for each trial. Each individual schematic represents a different time the tool was picked up and used. For example, in Trial 1 a tool was picked up and used on seven different occasions. On each occasion, the surfaces where the ply are formed are highlighted in blue and the edges in red

that when the laminator changed their goal for the lamination task from completion of the task to the highest possible quality to completion of the task in the fastest possible time, but still to an acceptable quality, the use of their tools decreased. It was also noted that in Trial 1 the laminator had used two of different tools but then in Trial 4 only one was used, in Fig. 1 the tool used has been highlighted with an asterisk. This suggests that how a laminator uses their tools is aligned with

the goals of the layup task. In a more general context, previous research has also shown that changing goals of a task impacts the behavior surrounding tool use.¹⁸ These trials raise the question of why the laminators habitually use their tools despite them slowing the laminator down.

It is significant that the laminator reduced the use of their tools because it is thought the tools are their feedback metric in force and visual quality. In all of the trials except

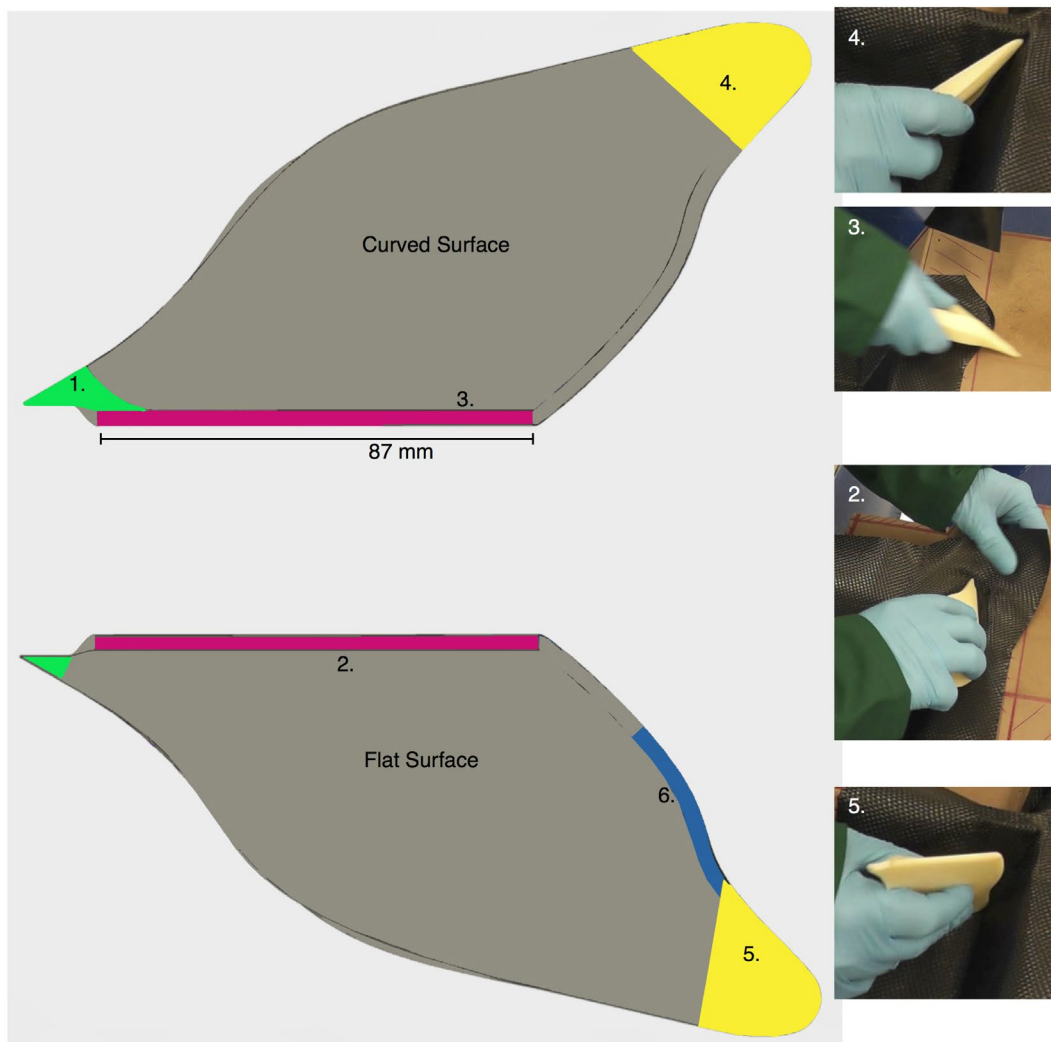


Figure 9 The six different geometrical features that were used for forming a ply during the trials the tool was used for. The geometrical features on the different surfaces that are coded with the same color have been numbered a different feature because the use of it required the laminator to use a different grip. The images on the right-hand side have been included to clarify this point, and the number on the image highlights the feature being used

Trial 5, tools were used to do the final consolidation of the forming process. The disrupted learning due to the change in tool between Trials 4 and 5 could explain the difference in behavior. The observations from the video suggest that the tool use is coupled with the laminator's satisfaction that the layup task has been performed to the highest possible quality. An evaluation of quality assessment was not conducted beyond the anecdotal with these trials, but should be considered with future trials.

Table 2 shows for the other trials the tools were used for a similar percentage of the total time taken to complete the layup task. Therefore, in Trials 5 and 6 in order to achieve a similar time to Trial 4 the laminator's use of the prototyped tool was not dropped and they could retain the use of their quality metric. These initial trials suggest it is possible that the use of a standardized tool has the potential to be preferable from both the perspective of a laminator's job satisfaction and the capability of production. The measurement of variables to explore this possibility will be incorporated into future trials.

It is thought that the links between manual tools and the formation of an acceptance criterion are worthy of further investigation as it could explain why the laminators habitually use their tools. In practice, the use of a standardized tool could form a geometrical acceptance criterion. In this scenario, the tool would also be used to physically represent a designer's physical constraints for geometrical features.

Mold geometry and tool use

This section attempts to understand and explain how the tools were actually used in each of the trials. This is done with reference to Fig. 8. In Fig. 8, each schematic of the mold represents an occasion a tool was picked up, used and then put down again for the trials. It is important to understand how and why a tool is being used for the development of instructions sheets, for a standardized tool, that have captured the knowledge of an expert laminator.

The results in Fig. 8 show that each time the laminator approached the layup trial, the exact technique they

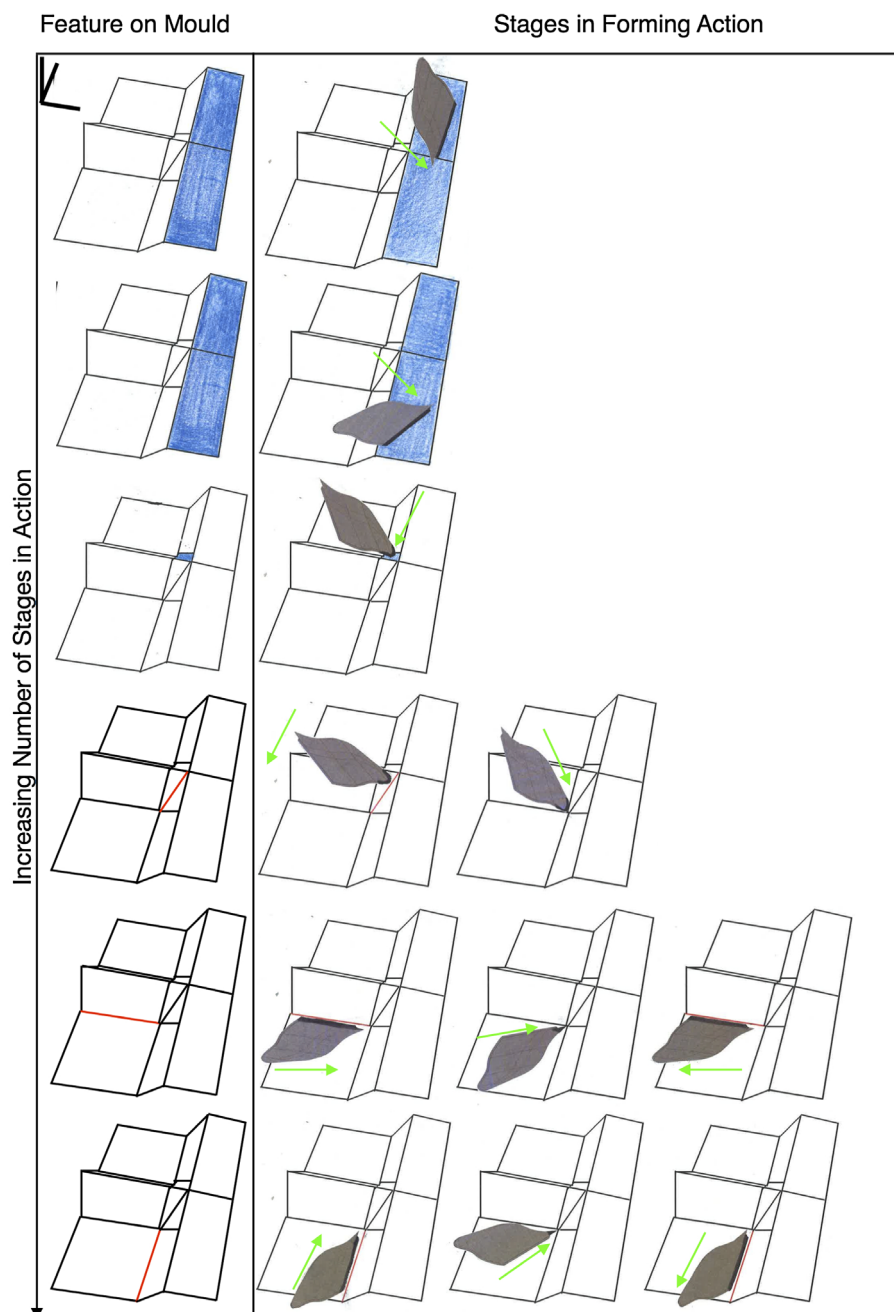


Figure 10 A suggestion for how different tool and mold features could be coupled together, with a suggestion for a forming action. The feature of the tool to be used is highlighted in black, the edge or surface of the mold is highlighted in red or blue, respectively, and the green arrow suggests a direction of motion and angle of attack for the tool. Some of the actions have more than one gesture and use more than one feature on the tool. For these actions the schematics should be read across the row. Not to scale

employed and the number of times they picked up and used their tools were different. This was despite the same starting procedure, defined by a datum, being followed. However, they all show the general trend that during the task the laminator moves away from the starting point and then returns there for consolidation. The variation seen between trials in the propagation is being attributed to natural variation. The development of a layup sequence and instructions will be the subject of future experiment design, to explore this variation further. However for these trials, it was beneficial to

capture the laminator's expertise on the forming route they employed, and their expertise will be sought for future experiment design.

The first time the laminator used the prototyped tool (Trial 2) (Fig. 8), shows it was picked up more times than tools in Trial 1. This is expected, as the laminator would have a level of uncertainty and learning involved with using the tool. Figure 8 shows the prototype was picked up and used on eight different occasions in Trial 2 and five different occasions in Trial 3. In between Trials 2 and 3 the prototype was sanded, it is

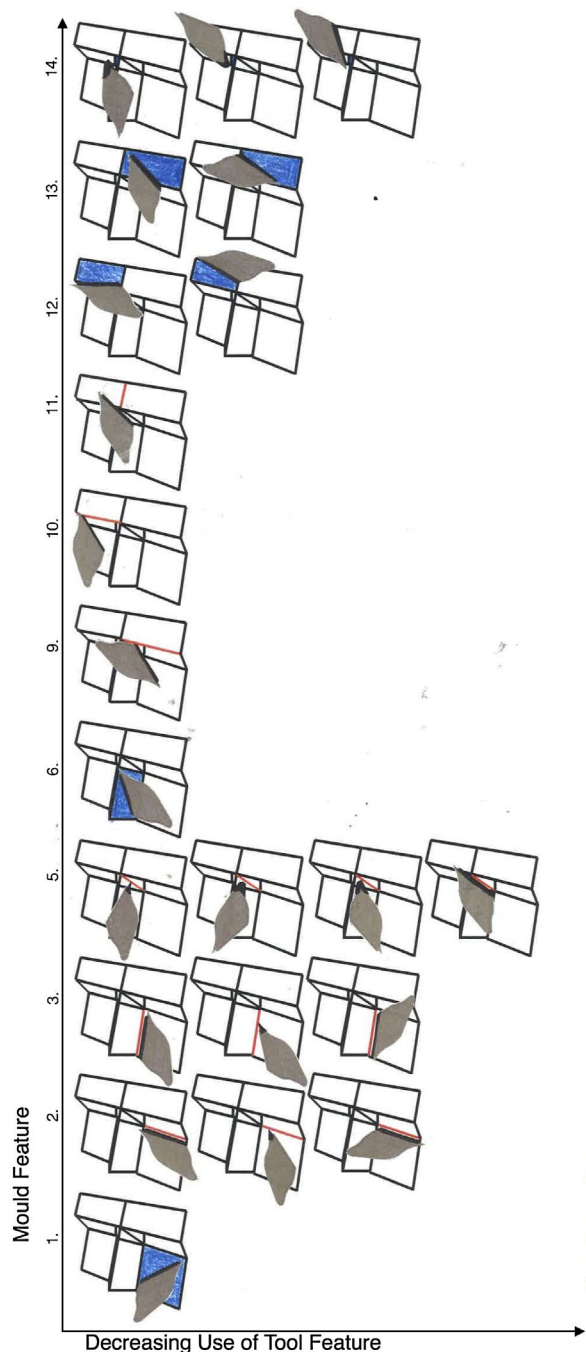


Figure 11 Use of tool features to form ply on specific mold features during Trial 6. The analysis was done to develop both the design of the prototype and its instructions for use. The feature of the tool used has been highlighted in black and the edge or surface formed have been highlighted in red or blue, respectively. For each individual mold feature, the decreasing use of a tool's feature has been represented. Not to scale

believed this subtle change in its geometry has allowed the laminator to reduce the number of times they picked up and used the tool. The schematics for Trial 3 support this belief as they show that each time the tool was used more regions on the mold have been formed.

In Trial 4, the number of separate occasions a tool was picked up and used (eight times) has increased with comparison to Trial 3 (five times). It is thought that this increase in the

number of different occasions of use in Trial 4 is due to both the fact the goal of the layup task was changed and the fact the laminator used their tools. During this trial, it was observed that the laminator did not use their tools for very long each occasion they were picked up, this observation is supported by the reduced percentage of tool forming for Trial 4 in Table 2.

For Trials 5 and 6, the prototyped tool shows a reduction in the number of separate occasions it was used compared to Trial 4. Again the schematics in Fig. 8 would suggest this is because on each occasion the laminator was forming more regions of the mold. Again this analysis is complemented by the observation that during these trials the prototype's form allowed the laminator to move it around in their hand and use its different feature in one occasion of being picked up.

Figure 8 shows in Trial 5 the laminator used the prototype on more occasions than in Trial 3. This reinforces that the laminator was still learning how to use the prototype and that the learning was interrupted by Trial 4.

From this attempt to understand how the tools were used in practice, it is believed five areas that impact how the laminator interacts with the tool, and consequently their behavior can be extracted. These are:

- The form of the tool.
- The mold geometry.
- The layup task (directly related to the mold geometry).
- The laminator's goal for the layup task.
- The laminator's individual learning.

Coupling the prototyped tool's features with mold features

The results from the trials with the prototype showed that it had six features that were used. As shown in Fig. 9 both surfaces of the tool were used. The surface that was used depended on how the laminator gripped the tool and approached forming that particular region of the mold. In Fig. 10, suggestions for how the prototype and mold geometry are coupled are presented. These suggestions (Fig. 10) demonstrate the same geometrical feature on the prototype (e.g. 2 and 3) but with a different grip and angle of attack to the mold. This implies that forming certain geometrical features on a mold requires flexibility in the tool's direction of forming, and therefore in how it is gripped.

Figure 10 suggests the laminator has only highlighted four features of the tool coupled to a feature on the mold. However, the analysis of Trial 6 (Fig. 11) shows that the laminator used five different features of the tool and often used more than one feature for particular mold geometries. However, there are similarities between the most popular decisions for tool use during the layup task and their returned comments afterwards.

It was anticipated that greater variation would be seen during the layup task (Fig. 11) than what was suggested in returned comments (Fig. 10). During the layup tasks, the laminator was not supported through the learning process and consequently their decision-making, that surrounds the forming, cannot be expected to be consistent. However, this inconsistency has been traded for knowledge capture about how an expert laminator handled the prototype.

To form the mold feature numbered 5, the laminator suggested one feature on the prototype (Fig. 10), however in

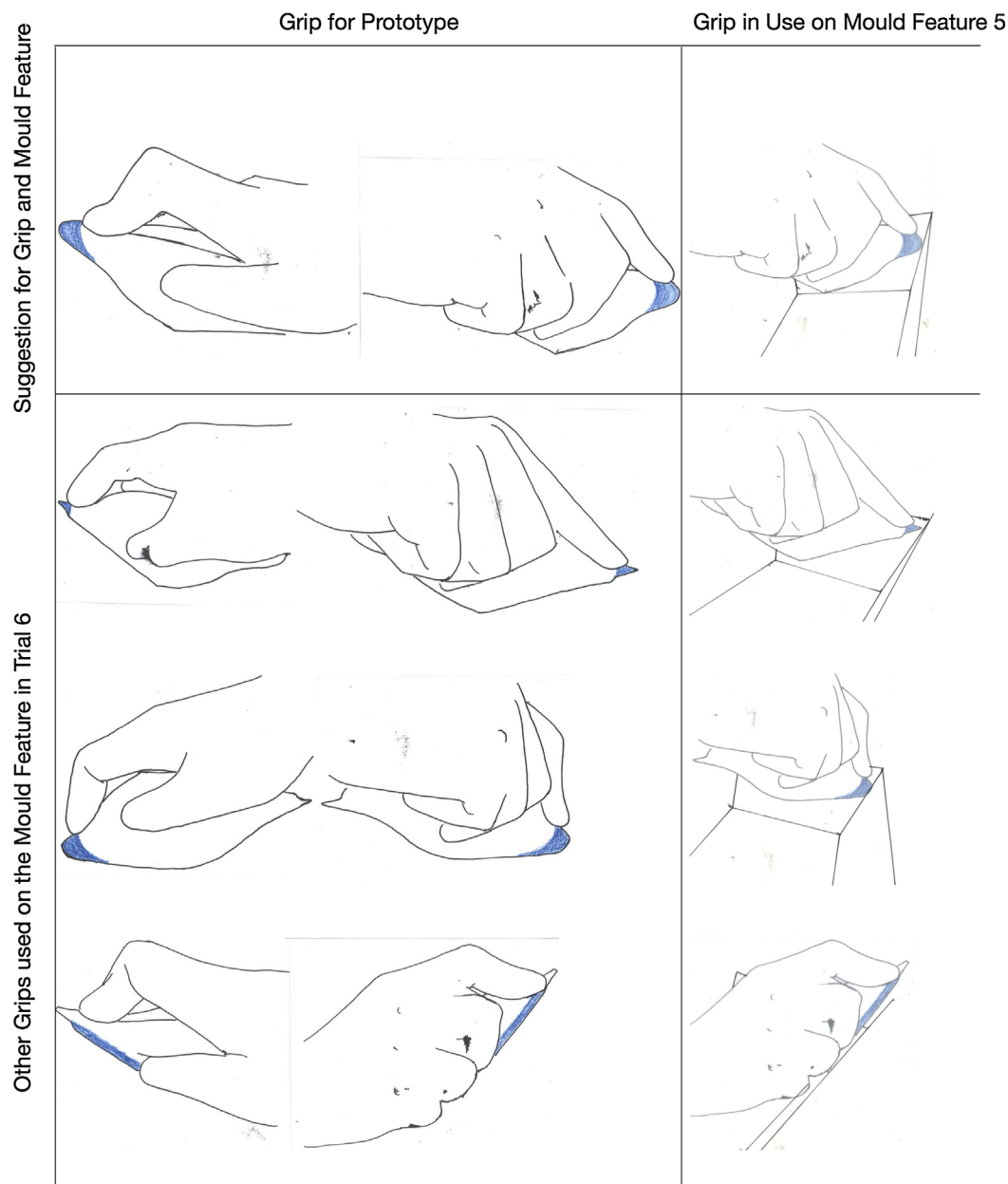


Figure 12 The laminator's suggestions for how the prototype should be gripped to form feature 5 on the mold. Presented beneath the suggestion are the other grips that the laminator used for forming feature 5 in Trial 6

reality four were used (Fig. 11). Figure 12 presents the suggested grip for the mold feature numbered 5 and then the other three grips that were observed in practice. Of these four, two were the same feature but on different surfaces, demonstrating the laminator had been gripping the tool differently, and therefore approaching the task differently when the ply had been reformed. However, the fact the laminator has proposed just one, suggests that they are used with a different level of ease.

These results support the suggestion that a solution borders on the realm of skills and training. It is not enough to prescribe a tool – the laminators need support with the decisions that they take during the task. During these layup tasks, the laminator was not supported during their learning curve. The results testify that whilst maybe there are patterns

in how they approached the task or used the features of the tool with the mold, how the actual task was approached each time was different. These results also highlight that to use a standardized prototype in a training environment developed instructions are required. The laminator's knowledge captured in these trials will need to be used to develop instructions for its use in such an environment.

For a solution to move into skills and training the coupling of hand, tool, and mold geometries required to facilitate the development of a lamination technique are needed. Previous research has stated that "grips are voluntary actions: to grip is a decision",¹⁹ therefore it is suggested this coupling is essential if the laminator is to be supported. This is challenging because if the instructions are too prescriptive the laminator might be left without their ability to make informed decisions on the fly,


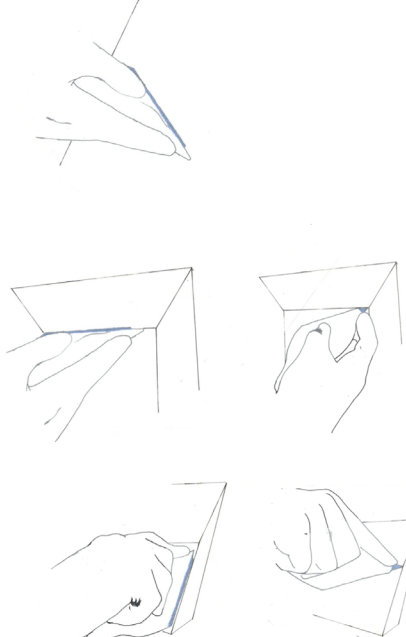

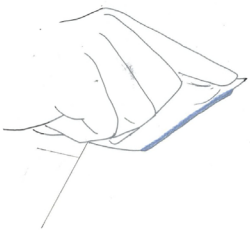


Grip for Prototype	Mould Feature	Grip in Use on Different Mould Features
	<p>12, 13</p> <p>3</p> <p>2</p>	
	<p>12, 13</p>	
	<p>5, 14</p>	

Figure 13 From the couplings suggested in Figure 10 here the laminator's suggestions for how the prototype should be gripped to form the different mold features

and therefore unable to correct unforeseen deviations. Here the consideration of a laminator's values becomes particularly important, as previous research has shown attempts to standardize hand layup has had negative implications for a laminator's motivations.²⁰ Therefore, in future studies a laminator's job satisfaction will be used as a metric.

To conclude, presented in Fig. 13 are the grips to use the prototype as suggested by the laminator in Fig. 10. These grips and how to use them on mold geometries will form the initial part of developing instructions that can be used in a training environment for laminators.

Future work

The prototyped tool can be further developed to generically improve a concept that could be supportive to the growth of the composites industry. Potential routes for development are skills and training, and the composites design process. A

common theme to these routes is how a standardized tool can be used to facilitate human interaction. Consequently, beyond these routes other possibilities for further work could target how the interaction can be changed, for example by making the tool responsive.

Skills and training

Results suggest that it would be worthwhile conducting layout trials that are slightly different in structure. Ideally, these would support the laminator through the learning process of a new tool, and consequently be aiming to reduce the variation in how the laminator approaches the tasks. It is envisaged that supporting the laminator through the learning process would require developing instructions for use. Figure 11 gives an indication of the ease of use of the prototype's features for a mold geometry, and the popularity of a feature and Fig. 13 the actual grips to use a feature of the prototype.

The form that these instructions might take is currently unclear. However, this fits in well with investigating how these tools could be coupled with a skills and training program for both expert and novice laminators. To deliver this skills training, and track a knowledge base, an approach is suggested allowing both existing knowledge to be exploited and developing knowledge to be added. For example, a similar approach is being developed by “La Bullipedia” an online platform for chefs.²¹ To facilitate the knowledge being exploited the form that it is communicated in, and how it is interacted with requires research.

Composites design process

It is believed the design process of a composite product is extended into and problem solved in production. The tools made by laminators are a manifestation of this issue between material, form, and human. The prototyped tool could be used as a protagonist to further investigate the composites design process, as it is an example of an outcome that could better inform the development of design for manufacture.

By introducing the concept of a standardized tool, it is possible to envisage that the design of a product, mold, the manufacturing instruction sheets, drape activity, and tool can become complementary design processes. The future work lies in structuring the captured knowledge around these processes and developing a design for manufacture so a designer can interact with it.

Conclusions

In this paper, a prototyped tool that was designed for a laminator has been tested in layup trials. The laminator's own tools were used as the control for the layup trials. The initial findings have suggested that the tools are used as a feedback for quality, and how the tool is used is aligned with the goals of a layup task. The prototyped tool allowed the laminator to achieve comparable layup times as when their tools were used. To achieve the faster layup times with their tools the laminator had to decrease the use of them, and hence the quality could be negatively impacted upon. With the prototyped tool, the use of the tool and hence the quality feedback was retained in contrast in the trial where the laminator's own tools were used. These trials raise the question of why do laminators habitually use their tools despite them slowing the laminator down.

The trials also showed that the geometric features on the prototyped tool and the mold were coupled. However, variation was still seen in how the laminator approached the layup tasks. This implies that the development of a tool should be linked with the skills and training of laminators and the development of instructions, rather than being purely prescriptive.

This is the first time a standardized tool for composites has been investigated. Beyond being supportive to the training of laminators, and ensuring production control this research is suggesting a standardized tool is a mechanism to develop a design for manufacture for composites, and integrate a laminator's knowledge into the design process.

Conflicts of interest

No potential conflict of interest was reported by the authors.

Acknowledgements

The author gratefully acknowledges the support of the EPSRC through the ACCIS Centre for Doctoral Training [Grant No. EP/G036772/1] and the EPSRC Centre for Innovative Manufacturing in Composites (CIMComp) [Grant No. EP/I033513/1].

References

1. Composites Leadership Forum: 'UK composites 2013: a study into the status, opportunities and directions for the UK composites industry'; 2013, UK, Composites Leadership Forum and Department for Business, Innovation and Skills.
2. P. Lewis: 'Skills and training for composites manufacturing and use in the UK: an analysis'; 2013, London, UK, The Gatsby Charitable Foundation.
3. A. P. Chatzimichali and K. D. Potter: 'Growth through material: an exploratory study in the development of the composite industry'; In Business Systems Laboratory – 2nd International Symposium 'Systems Thinking for a Sustainable Economy. Advancements in Economic and Managerial Theory and Practice', 23–24 January 2014.
4. D. Crowley, C. Ward and K. Potter: 'A status of acceptance criteria and process requirements in advanced composites manufacturing, and whether they are fit for purpose'; Rome, Italy, 2013, Proc. SAE Technical Paper 2013-01-2144, doi:10.4271/2013-01-2144.
5. C. Ward, D. Lukaszewicz and K. D. Potter: 'Exploring the manual forming of complex geometry composite panels for productivity and quality gains in relation to automated forming capabilities'; 2011, Proc. SAE Technical Paper, 2011-01-2547.
6. 'Bigger, Faster, Cheaper', JEC Composites Magazine, January–February 2014, 86, 23–24, JEC Composites.
7. T. Kikuchi, H. Hamada, A. Nakai, A. Ohtani, A. Goto, Y. Takai, A. Endo, C. Narita, T. Koshino and A. Fudauchi: 'Relationships between degree of skill, dimension stability and mechanical properties of composite structure in hand lay-up fabrication method'; 19th Int. Conf. on 'Composite materials', Montreal, Canada, July 2013, Canadian Association for Composite Materials and Structures, 8034–8046.
8. LamRight LLC, Laminating tools, 2008, available at <http://www.lamright.com/products.asp?cat=14> (accessed 13 July 2015).
9. Bojo Tools, Composite hand tools, 2011, available at <http://www.bojoinc.com/index.php/composite-hand-tools.html> (accessed 13 July 2015).
10. L. D. Bloom, M. K. Elkington, C. Ward, A. Chatzimichali and K. Potter: 'On prepreg properties and manufacturability'; Proc. 19th Int. Conf. on Composite Materials, Montreal, Quebec, Canada, July–August 2013, Canadian Association for Composite Structures and Materials, 4397–4409.
11. M. K. Elkington, C. Ward, A. Chatzimichali, L. D. Bloom and K. Potter: 'Understanding the lamination process to improve composite manufacturing'; Proc. 19th Int. Conf. on Composite Materials, Montreal, Quebec, Canada, July–August 2013, Canadian Association for Composite Structures and Materials, 4385–4396.
12. M. Such, C. Ward, W. Hutabarat and A. Tiwari: *Proc. CIRP*, 2014, **25**, 122–131.
13. D. Zakay and J. Shub: *Ergonomics*, 1998, **41**, (8), 1115–1128.
14. S. Howick and C. Eden: *Int. J. Prod. Res.*, 2007, **45**, (12), 2775–2797.
15. Advanced Composites Group, MTM49 Prepreg data sheet, 2006, available at <http://www.lavender-ce.com/wp-content/uploads/pds1059-mtm49series-7.pdf> (accessed 13 July 2015).
16. D. Nembhard: *Hum. Factors J. Hum. Factors Ergon. Soc.*, 2000, **42**, 272–286.
17. D. Nembhard and M. Uzumeri: *IEEE Trans. Eng. Manage.*, 2000, **47**, (3), 370–378.
18. C. Baber: 'Cognition and tool use: forms of engagement in human and animal use of tools', 1st edn; 2003, USA, Taylor and Francis.
19. R. Sennett: 'The Craftsman', p. 151, 1st edn; 2008, UK, Penguin Books.
20. D. Crowley, C. Ward, K. Potter, O. Kasyutich, K. Jonas and N. Jennings: 'A study into composites laminators' motivation'. Advances in sustainable and competitive manufacturing systems, 971–984; 2013, Switzerland, Springer International Publishing.
21. La Bullipedia, Online database for gastronomic knowledge, 2012, available at <http://www.bullipedia.com> (accessed 13 July 2015).