ROBOT-FORMING OF PREPREG STACKS - DEVELOPMENT OF EQUIPMENT AND METHODS

Andreas Björnsson[1], Marie Jonsson[2], Jan Erik Lindbäck[3], Malin Åkermo[4] and Kerstin Johansen[5]

[1]Manufacturing Engineering, Linköping University, 581 83 Linköping, Sweden
Email: andreas.bjornsson@liu.se, Web Page: www.iei.liu.se/indprod
[2]Swerea SICOMP, Manufacturing and Simulation, Bröderna Ugglas gata Hus 208 581 88 Linköping, Sweden. Email: marie.jonsson@swerea.se, Web Page: www.swerea.com/sicomp
[3]Engineering, Aerostructures, SAAB, 581 88 Linköping, Sweden
Email: jan-erik.lindback@saabgroup.com, Web Page: www.saabgroup.com
[4]Aeronautical and Vehicle Engineering, Royal Institute of Technology KTH, Teknikringen 8, 100 44 Stockholm, Sweden. Email: akermo@kth.se, Web Page: www.kth.se
[5] Machine Design, Linköping University, 581 83 Linköping, Sweden
Email: kerstin.johansen@liu.se, Web Page: www.iei.liu.se/machine

Keywords: prepreg, forming, robot, automation

Abstract

Within the aerospace industry the manufacturing of composite components with complex shapes, such as spars, ribs and beams are often manufactured using manual layup and forming of prepreg material. Automated processes for prepreg layup and efficient forming techniques like vacuum forming are sometimes difficult to employ to these type of products due to technical limitations. This paper describes the development of tools and the forming sequence needed to automate sequential forming of a complex shape using an industrial robot. Plane prepreg stacks are formed to the final shape using a dual-arm industrial robot equipped with rolling tools. Tests show that the developed tools and the employed sequence can be used to form stacks to the desired shape with acceptable quality.

1. Introduction

The use of Carbon Fiber Reinforced Polymers (CFRP) increases steadily within the aerospace industry as the material provide a possibility to design strong lightweight structures with tailored material properties. Alongside with an increased use of the CFRP-materials, automated manufacturing processes have been developed and today Automated Tape Laying (ATL) and Automated Fiber Placement (AFP) are commonly used for automated layup of unidirectional (UD) prepreg material. However, both ATL and AFP are associated with high capital investments and they are limited in their ability to layup onto highly curved molds or to place small pieces of prepreg [1]. Small, intricate parts such as spars, ribs and brackets are in many cases too complex to be efficiently laid up onto the final curing mold using ATL or AFP [2] and therefore this type of complex components is often manufactured manually. Manual labor is however costly; cutting and manual layup of plies can account for 40-60% of the manufacturing cost depending on part size and complexity [3]. An alternative to layup directly on the curing mold, is a two-step process where prepreg is laid up to form a flat multi-layer laminate called a stack, which is subsequently formed to the final part shape in a separate forming process. The two step process greatly reduces the layup complexity as the layup is transformed from a three-dimensional to a two-dimensional case. The layup of prepreg stacks can be made manually, or by using automated solutions such as ATL, AFP or dedicated layup systems [2].

Excerpt from ISBN 978-3-00-053387-7

There are a number of forming processes that can be used to achieve the final product shape. Vacuum forming is a commonly used process where a prepreg stack is placed onto a mold with the desired product shape. The stack is covered with a rubber diaphragm and vacuum is applied under the diaphragm which forces the stack to assume the mold geometry. Heat lowers the resin viscosity and can be used to facilitate the forming process [3]. Radiant heating using infrared lamps is effective for thin laminates since carbon prepreg has a black surface and reasonable good heat conductivity [2]. Heat assisted vacuum forming is known as Hot Drape Forming (HDF). The possibility to use vacuum forming or HDF for forming a certain product is much dependent on the formability of the selected prepreg material, the stacking sequence used i.e. the fiber orientation of the individual layers within the stack, as well as the desired product geometry. Double curved shapes and beams with flanges can be difficult to form using these methods.

A forming method that offers a possibility to form complex shapes is sequential forming where the prepreg stack is placed on a mold with the desired geometry and is then gradually formed using tools like rollers and scrapes. Sequential forming is usually a manual operation but it can be automated using industrial robots as is the scope of this paper. Robot-forming of a spar with a recess area has previously been investigated in [4]. In this case, UD prepreg stacks with a thickness of up to 5 mm were formed onto the mold in one forming step using a scraper. Heating was applied to simplify forming, however, a very slow forming rate was still needed, especially in the recess area. Different forming sequences were investigated and the experiments were accompanied by forming simulations in order to understand the observed phenomena. Robot-forming was also a part of the Triple Use project [5] where a robot used scrapes to sequentially form a pre-compacted 20-layer stack onto a mold with modified U-beam shape. In this case, the stacking sequence made it impossible to form the part using HDF due to wrinkling issues. The robot-forming process produced a consistent result without wrinkling and at a cycle times which were up to par with manual forming. The robot-forming process that is the focus of this paper, and that will be described in more detail in the coming sections, is developed for forming of thin stacks onto an Ω-shaped mold using rolling tools instead of scrapes.

Paton [2] conclude that the most important deformation mechanism in forming of UD thermoset prepreg laminates is interply slip, also known as interply shear. This is the relative movement between individual prepreg plies in the laminate during forming over single curvatures as for example when forming a prepreg stack over a radius [2]. On the other hand, forming in terms of draping, where the material area need to conform to a varying surface area of the mold cannot be obtained without intraply shear. Both interply slip as well as intraply shear are viscoelastic mechanisms depending on both resin viscosity, prepreg architecture in terms of e.g. existence of toughening thermoplastic particles [6, 7], forming speed and the compaction pressure on the laminate. Furthermore, Paton [2] point out that formed shapes typically revert partly towards their original flat shape if removed from the tooling without being stabilized. The time dependency and shape recovery is much dependent on the prepreg resin and the thermal history of the material as well as the architecture of the material. Concerning forming induced defects Paton [2] state that the most common defects that occur when forming carbon-epoxy prepreg laminates are various types of wrinkles. Experiments have shown that the layup sequence of a prepreg stack has a dominant effect on wrinkle development during forming [8]. Wrinkles however have different origins [9]; locally induced wrinkles caused by single layers in compression due to non-favorable shearing, can sometimes be avoided by local manipulation of the prepreg interlayers [10]. Global wrinkling caused by excessive material, on the other hand, can only be avoided by shearing the excessive material towards edges or into areas that otherwise would be short of material.

2. A Cell for Automated Layup and Forming of Prepreg Stacks

This paper focuses on automated sequential forming using an industrial robot, i.e. robot-forming. The robot-forming process is part of an automated manufacturing cell that also includes automated layup of prepreg stacks [5] and automated removal of the prepreg backing paper [11]. The aim of the cell is to demonstrate how the manufacturing of complex shaped products, like beams and stiffeners, can be

Excerpt from ISBN 978-3-00-053387-7

automated. The developed solution should meet the criteria that are used in industry today i.e. produce parts meeting the same quality requirements that are applied to similar parts manufactured by hand. For the development and testing of the automated cell a test object is used. The test object, illustrated in Figure 1 below, is an Ω-shaped beam with a geometry that resembles a real case reference part in full scale production.

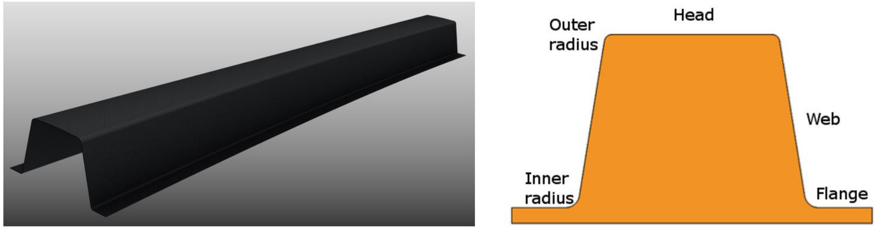


Figure 1: The test object, a Ω-shaped beam, and the cross section of the mold used to form it.

The test object consists of seven layers of approximately 0.2 mm thick, aerospace graded, UD carbon fiber-epoxy prepreg stacked in a sequence that covers the 0°, 45°, -45° and 90° fiber orientations. The prepreg is comprised of Intermediate Modulus (IM) carbon fibers and an epoxy matrix that cures at 180° C. The test object has a cambered head and curved web and is designed to a shape that can be manually formed without wrinkling. The manufacturing process for the reference product starts with manual stacking of prepreg plies. The stacks only consist of two layers of prepreg to simplify the subsequent manual forming process. Thin stacks are simpler to form since they easier conform to the mold geometry and less forming pressure is needed. After a stack has been manually formed using scrapers and other hand tools it is consolidated on the mold by covering it with a vacuum bag, and applying vacuum for at least ten minutes. After the consolidation the next two-layer stack is formed on top of the already formed stack. In case of an uneven number of layers in the total stack, single plies might be formed. After each consolidation step the part is visually inspected to make sure that the stack follows the mold contour tightly. The inner radii are checked to make sure that a phenomena called bridging, where a small gap is formed between the prepreg and the mold in the inner radius because the stack does not follow the mold contour all the way down in the radius, has not occurred. The formed stack is also checked for wrinkles, bubbles and misaligned fibers. Wrinkles, visible fiber misalignment and large bubbles are not allowed but small bubbles or blisters called puckers can be accepted. The manual manufacturing process of the reference product has been the starting point for the development of the automated solution for the test object and the same quality evaluation criteria have been applied to evaluate the results of the automated forming process.

3. Development of Tools and Forming Sequence

The two most important aspects in developing a robust robot-forming process are the design of the robot mounted end-effectors, called forming tools, and the forming sequence i.e. the robot motions and in which order that they are performed. These two aspects are co-dependent, tool geometries can for example limit the ability to perform certain motions and a desired motion might require a specific tool design. Several different concepts for forming tools have been developed and tested in manual and robot based forming tests. Along-side the tool development the forming sequence has been established and results from preliminary tests have been used to refine both the tools and the sequence. The starting point for establishing the robot-forming sequence is the sequence used for the manual forming of the reference product, which has been adapted to suit the developed tools.

In the automated manufacturing cell, a Yaskawa SDA10 dual-arm robot with a potential payload of 10 kg per arm is used for the robot-forming process. In order to reach all relevant positions during

Excerpt from ISBN 978-3-00-053387-7

forming the mold is placed on a movable platform providing access to both sides of the mold. Infrared heating elements are placed on two sides of the mold to provide heating during the forming process. The heaters are controlled by a temperature sensor and a regulator to avoid overheating. The sensor only measures the temperature of a small area of the stack and to check the full length of the stack an additional handheld thermometer was used. This showed an uneven heat-distribution in the laminate with the center parts heating up faster and holding a higher temperature than the peripheral areas. The setup used during the robot-forming tests is shown in Figure 2 below.

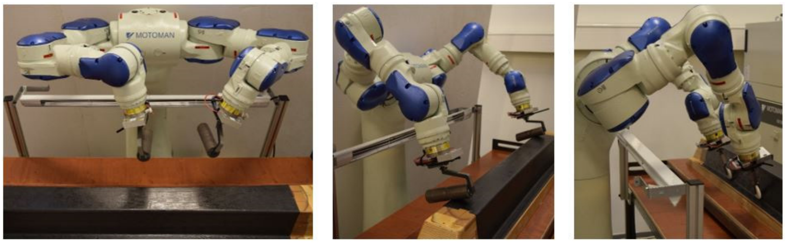


Figure 2: The robotic cell used for the forming tests shown from different angles.

In previous robot-forming projects gradual deformation of the prepreg stack has been made using a scraper to apply pressure on the prepreg stack [4]. For this project, an alternative approach with rolling tools has been tested. Tests of several prototype tools showed that in order to ensure continuous and controlled contact between the tool and the stack during the forming motions, some sort of compliancy need to be built in the tool. The compliancy can help to compensate for variations in material thickness and robot path accuracy. It also reduces the risk of damages to the tools or material in case to high pressure is applied if any deviations occur. The compliancy can be built in the roller itself by using non-rigid materials or it can be obtained by using a spring-loaded holder in combination with a rigid roller. Early tests indicated that compliant rollers with non-rigid material resulted in a better forming process, especially around the outer radius. From the tests it also became clear that wide rollers reduce the number of required passes required to form each area of the beam. However wide rollers cannot be used to form the inner radius and therefore a separate tool is required for this specific task. Several tests and design revisions resulted in the tools that are shown in Figure 3

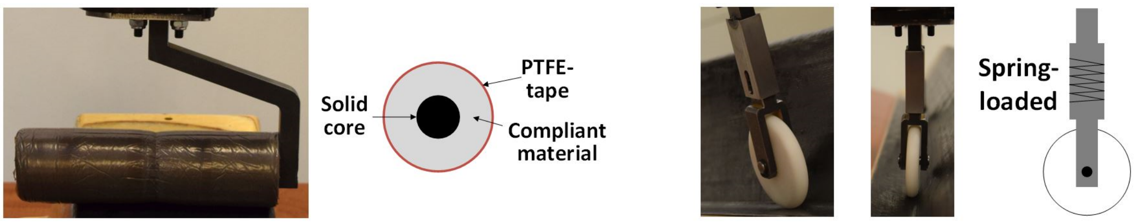


Figure 3: Left, the wide roller used for most motions in the forming sequence. Right, the tool used for forming the inner radius.

The large roller is slightly wider than the head of the beam and consists of a solid shaft enclosed in a compliant foam-material that is covered with a Teflon (PTFE) surface. The roller is mounted on a stiff arm and attached to the robot arm using a simple tool exchange system. The smaller roller, used for forming the inner radius, is made up of a small plastic disk with an outer edge that is rounded to the same radius as the beam's inner radius. The disk is mounted on a spring-loaded holder that can be attached to the robot's tool exchange system.

Excerpt from ISBN 978-3-00-053387-7

Alongside the tool development the forming sequence has been developed iteratively with a number of manual and robot-based tests to evaluate different approaches. The sequence is inspired by the manual forming process but designed to suite the chosen tool design. The sequence has been adopted to suite the dual-arm robot used for the tests and it has been designed to allow for both arms to form different areas of the beam at the same time as a way to lower the process time. Much of the design effort has been dedicated to find tool angles, motions and how and where to apply pressure in order to achieve a good forming result. The speed of the movements has not been thoroughly tested and analyzed. The speed is in the range of 30-70 mm/s during forming however, it might be possible to increase the speed. The forming sequence used for the final tests is illustrated in Figure 4. and explained in further detail below.

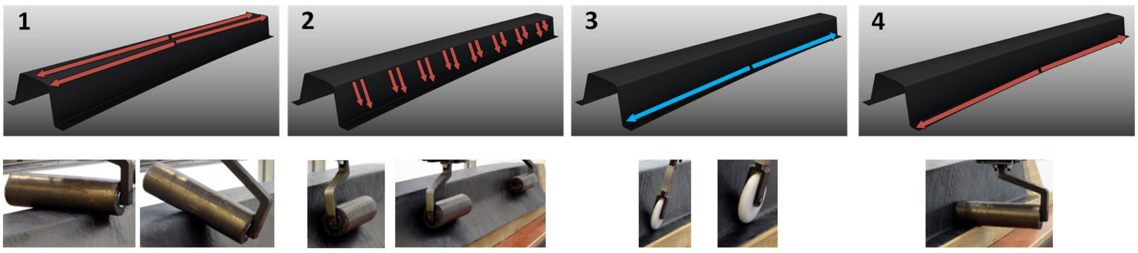


Figure 4: The forming sequence and how the tools are positioned during the forming motions.

1. In the first part of the forming sequence the wide roller is used. The roller secures adhesion between the stack and the head of the mold with a minimum of passes, reducing the cycle time. The roller is held parallel to the head-surface and rolled from the center outwards to the end of the beam. This motion is followed by a step where the roller follows the outer radius at an angle with a pressure that deforms the compliant foam in the roller slightly around the radius which forces the stack tightly around the outer radius.
2. In the second part of the forming sequence the web is formed using the wide roller. The roller starts in the center of the beam and follows the web from the outer radius approximately half way down to the inner radius. This motion is repeated, with a small overlap, from the center and out to the end of the beam. After reaching the ends of the beam, the same motion is repeated once more but this time the motion goes from the outer radius almost all the way down to the inner radius but without touching the flange.
3. For the third part of the forming sequence the forming tool is changed to the small roller. The robot positions the disk so that the stack is in contact with the inner radius in the center of the beam. The disk is then moved along the inner radius from the center out towards the end of the beam. This motion is repeated twice to make sure that the laminate fully deforms to the inner radius in order to avoid bridging.
4. To execute the final part of the forming sequence the small roller is exchanged for the larger roller. The large roller is rolled along the flange from the center of the beam and outwards.

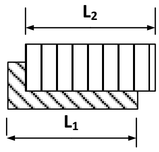
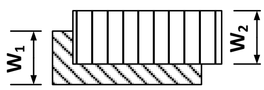
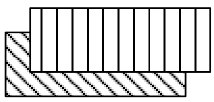
Both robot arms are equipped with exactly the same type of tools and the arms are, as often as possible, working in parallel forming the right and the left part of the beam at the same time to reduce cycle time. One arm always starts forming from the center of the mold and once it has moved a safe distance from the center the other arm starts forming the other half. A small overlap between the motions performed with the left and the right arm is employed, as well as overlap between the movements when forming the web of the beam in order to make sure that all areas of the stack have been pressed by the rollers.

Excerpt from ISBN 978-3-00-053387-7

4. Results from Tests

Tests using the forming sequence and the tools described above have been carried out on four different stacks, called stack A-D. Information about the stacks is summarized in Table 1. The layers in each stack always have the same length and the layers are always centered on top of each other. Stack A contains two layers with fiber angles intersecting at 90°. In stack B the angular difference between the fiber directions in the two layers is 45°. Unlike stacks A and C the two layers in stack B have different width. The narrower layer is centered onto the wider layer. This yields a stack where the outer edges of the stack are one layer thick but the center part is two layers thick. Stack C contain three layers with two different fiber angles. Stack D is a seven-layer thick union of stack A, B and C. After each stack is formed it is covered with release film, breather and vacuum bag film and a vacuum is applied for at least ten minutes. The three thinner stacks (A-C) are formed on top of each other with a vacuum bagging process between the forming of each stack.

Table 1: Stacks used for the forming tests.

Stack Name	Number of Plies	Ply Length 	Ply Width 	Fiber Angles Crossing at  (in this example the fiber angles are crossing at 45°)
A	2	$L_1=L_2$	$W_1=W_2$	90°
B	2	$L_1=L_2$	$W_1<W_2$	45°
C	3	$L_1=L_2=L_3$	$W_1=W_2=W_3$	45° (2 plies with the same angle)
D	A+B+C=7			

The tests show that the two-layer thick stack A can be robot-formed with approved quality. The result of that forming operation is shown in Figure 5 below. The laminate adheres well to the forming tool around the outer radius and along the head, web and flange. No bridging was detected along the inner radius. Small bubbles were observed but these could be smoothed out using hand pressure and the bubblers were not visible after the vacuum bagging process. Small blisters, so called puckers, were observed on the web and the flange but they are considered to be acceptable, and are not a reason to reject the beam.

Figure 5: Stack A formed with approved quality result.

Excerpt from ISBN 978-3-00-053387-7

The same forming sequence and tools that yielded an approved forming result for stack A resulted in a non-approved forming result for stack B. Since the layers had different width the outer edges, which will be formed to the lower part of the web and the flange, only consist of one layer. During the forming of these areas the fibers twist, resulting in ripples on the flange as shown in in Figure 6a. Continuing the forming sequence by rolling the flange compress the ripples to wrinkles, as shown in Figure 6b. The result from the forming tests of stack B cannot be accepted due to the wrinkles. The fiber-misalignment at the lower part of the web and on the flange is also cause for rejecting the part. The forming of the three-layer thick stack C, seems to yield an acceptable quality. Some small defects were observed but they most likely derive from defects from the underlying stack B.

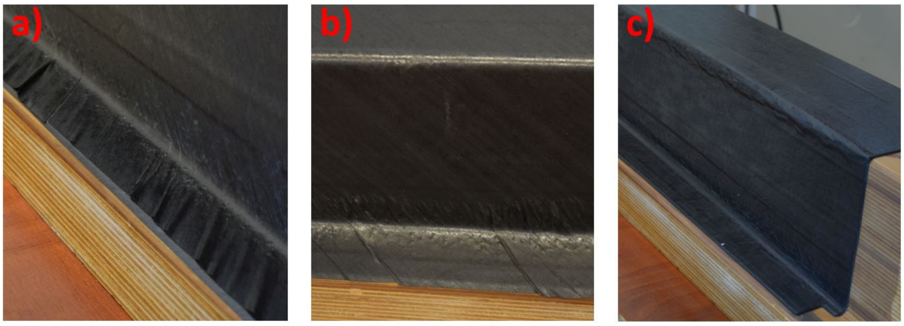


Figure 6: Examples of defects: a) Ripples b) Wrinkles c) Incorrect form of outer radius

To avoid forming of stacks that partly consist of a single prepreg layer, which is believed to be the source of the problems when forming stack B, the full seven-layer stack was formed in one step. Tests using the same forming sequence as described above resulted in problems when forming the outer radius and the web. After the seven-layer stack was pressed down over the outer radius and along the web the stack sprang back slightly as the forming tool was removed. Continued forming could not force the stack back into contact with the upper part of the web resulting in an incorrect form of the outer radius as shown in Figure 6c. No other defects, apart from the poor adhesion between the prepreg stack and the web of the mold were observed. The motions used for forming the outer radius and the web were altered to provide higher pressure towards these areas during forming. However, tests using the modified program resulted in almost the same spring back effect.

5. Conclusions and Discussion

The tests have shown that it is possible to use an industrial robot equipped with rolling tools to form prepreg stacks in a sequential forming process. A two-layer stack with two different fiber directions has successfully been formed to a Ω-beam shape without any defects. Forming of stacks where part of the stack consists of only one layer has shown to be challenging. One way to eliminate single ply forming is to stack thicker laminates. Forming of thicker stacks has been tested and despite some issues regarding spring back during forming it is an interesting approach that will be further investigated. Increased heating, changes to the mold surface in order to improve tack and forming with stiffer tools are believed to reduce the spring back behavior and will be tested in future tests. The temperature has, during the performed tests, varied along the laminate and it has been difficult to maintain a steady temperature of the laminate during the forming process. Since the temperature of the prepreg resin has a major effect on the forming behavior a more uniform temperature control during the forming process is desirable.

The compliant tools help to ensure that the tool is in continuous contact with the prepreg during the forming despite variations in material thickness and positional inaccuracy in the robot arms. The ability for the tools to deform has also simplified the robot programming task. For example, the somewhat

Excerpt from ISBN 978-3-00-053387-7

concave web has been formed with tools parallel to the beam rather than with an angle adapted to the curvature and the slightly convex head has been formed using a linear motion from the center towards the outer part instead of a curved path. However, this means that the level of pressure exerted by the tools during the forming is varying. A desirable development is to add a force sensor to the robot arm so that the robot can be programmed to follow a surface maintaining a certain pressure.

The use of a dual arm robot has in this case cut cycle time. The dual arm solution was chosen for the manufacturing cell mainly since the two arms provide increased flexibility in handing and manipulation of prepreg. The forming however could be done with most standard six axis industrial robots as long as the payload and reach are sufficient.

The test object presents a relatively simple forming case where the forming sequence could be inspired by manual forming of similar parts. For more challenging forming cases simulation of the forming sequence, as used in [4], might be required in order to reduce the number of physical tests.

Acknowledgments

The research presented in the paper has been part of the NFFP-program, funded by med Swedish Armed Forces, Swedish Defense Materiel Administration and Swedish Governmental Agency for Innovation Systems. The authors would like to thank the students Caroline Mattila, Fredrik Björklund, Gustav Ekbäck, Martin Johannesson and Victor Lindwall for their valuable help with tool development, robotic programming and testing and Tomas Andersson and Mikael Petersson for their help with testing.

References

[1] D.H.J.A. Lukaszewicz, C. Ward and K.D. Potter. The engineering aspects of automated prepreg layup: History, present and future. *Composites Part B: Engineering*, 43 (3):997-1009, 2012.

[2] R. Paton. Forming technology for thermoset composites. In: A.C. Long (ed) *Composites Forming Technologies*. Woodhead Publishing, pp 239-255, 2007.

[3] F.C. Campbell. *Manufacturing processes for advanced composites*. Elsevier, 2004.

[4] J. Sjölander and M. Åkermo, Automatic forming of composite aircraft beams. *Proceedings of the 5th International Swedish Production Symposium, Linköping Sweden*, November 6-8, 2012.

[5] A. Björnsson, J. E. Lindbäck, D. Eklund and M. Jonsson, Low-cost Automation for Prepreg Handling-Two Cases from the Aerospace Industry. *SAE International Journal of Materials and Manufacturing,* 9 (1), 2016.

[6] Y.R. Larberg and M. Åkermo, Interply friction of different generations of unidirectional prepreg plies. *Composites Part A: Applied Science and Manufacturing*, 42:1067–1074, 2011.

[7] Y.R. Larberg, M. Åkermo and M. Norrby, On the deformability of different generations of cross-plied unidirectional prepreg. *Journal of Composites Materials*, Vol. 46 (8):929-939, 2011.

[8] P. Hallander, M. Akermo, C. Mattei, M. Petersson, and T. Nyman, An experimental study of mechanisms behind wrinkle development during forming of composite laminates. *Composites Part A: Applied Science and Manufacturing*, 50: 54-64, 2013.

[9] J. Sjölander, P. Hallander and M. Åkermo, Mechanism for wrinkling of spars with joggle. *Composites Part A: Applied Science and Manufacturing*, 81:41-51, 2016.

[10] P. Hallander, Towards defect free forming of multi-stacked composite aerospace components using tailored interlayer properties. *PhD thesis at Royal Institute of Technology*, ISBN 978-91-7595-950-4, ISSN 1651-7660, 2016.

[11] A. Björnsson, J. E. Lindbäck, and K Johansen, Automated Removal of Prepreg Backing Paper - A Sticky Problem. *Proceedings of the SAE 2013 Aerotech Congress and Exhibition, Montréal, Canada,* September 24-26, 2013.