Land, Patrick and Branson, David T. and Crossley, Richard J. and Ratchev, Svetan (2016) Development of in-situ monitoring systems for the thermoforming of pre-preg composite laminates. In: MS&T16 Materials Science & Technology, 23-27 October 2016, Salt Lake City, USA.

DEVELOPMENT OF IN-SITU MONITORING SYSTEMS FOR THE THERMOFORMING OF PRE-PREG COMPOSITE LAMINATES.

Mr P Land[1], Dr D T Branson[1], Dr R Crossley[1], Prof S Ratchev[1]

[1]University of Nottingham, University Park, Nottingham, NG72RD

Keywords: Composites, Roll forming, In-situ Monitoring.

Abstract

Recent developments in automated composite manufacturing technologies, such as Automated Fibre Placement, AFP, and Automated Tape Layup, ATL, have enabled larger components to be produced efficiently, leading to an increased use of prepreg composites in aerospace. These processes are limited in the geometry that may be produced and therefore secondary forming processes are commonly required for implementation. There is, therefore, a need to improve reliability and increase forming capability using these processes, whilst ensuring that defects in the laminate are limited. Thermoforming of composite and polymer materials is a well-known forming method for use with polymers and polymer based materials. This paper will discuss the monitoring methods and results used in a typical thermoforming process based on experimental results from a composite material during Thermal Roll Forming (TRF). The focus of this testing is to characterise the effect of temperature and dynamic contact forces on the composite against the real-time development of defects such as wrinkles during TRF forming.

Introduction

Forming of composite laminates can take the form of a wide variety of technologies including but not limited to, diaphragm, autoclave and resin transfer moulding technologies, similar to these process Thermal Roll Forming, TRF, requires the use of both heat and pressure to form the material to a required geometry [1], where current limitations can be attributed to the balance between production rate and part quality in industries such as composites and additive manufacturing [2]. Often when high production rates are required it is difficult to form composite laminates without defects, particularly when more advanced geometries are required [2]. This problem is further intensified when looking at the large scale complex components that are used in modern commercial aircraft manufacture.

The focus of the work discussed in this paper is to take a new approach to how we look at the formation of composite components. Often, we look at how the material is behaving, what the ply's are doing, how they are interacting and how this may cause a defect [3]. This approach is founded on tried and tested materials forming approaches, however, when looking at the composites world each individual combination of matrix, reinforcement, and fibre orientation has drastically different properties and behaviours [4,5]. Because of this each individual composite component requires a detailed level of intricate study. This paper details a methodology to experimentally evaluate if there is a correlation between the parameters that are applied to the material and the formation of defects by in-situ monitoring of applied pressure, thermal distribution and process feed rate during production.

This study will focus on a single technology and material: the use of TRF on UD prepreg quasi-isotropic laminates to form a simple ramped geometry as a secondary process after AFP layup. The paper will discuss the methodology applied and how the parameters are applied and monitored, an overview of the test cell used and a case study of variable process feed rate forming and the resulting forming defect areas.

Methodology

The methodology behind this study is relatively simple, where the focus is on monitoring how the factors that go into a thermal forming process affect the quality of the part produced. In this specific technology the applied and resultant pressure will be monitored as well as the distribution of applied and resultant thermal heat transfer. In this study there is a 3rd parameter that we can control, the feed rate of the tool, this is the factor that we will vary in this study to show how this effects part quality and indicates the potential production rates of this technology.

Parameters Affecting Forming.

As mentioned above there are 3 main parameters that affect the forming process when looking at thermoforming of traditional materials such as thermoplastics [6, 7]. As such it is logical to consider that these factors will also affect the forming of thermoset composite materials, such as those used in this case study. These factors are the applied pressure, the Temperature distribution and the process rate (Feed Rate), in this section we will briefly discuss these factors and how they affect the forming process.

The feed rate in this case referrers to the speed at which the roller is forced over the mould tool to form the composite to the required geometry. The key theory here being that the greater the feed rate the higher the likely hood of a defect forming, this is largely due to the amount of time given for the matrix materials to shear and allow the fibres to move at an interply level [3]. However, in this specific example the nature of a thermoset composite is that the longer it is held at a forming temperature the more difficult it is to form [8], as such the feed rate must be carefully balanced and optimised.

Like the feed rate the applied pressure can directly influence the creation of defects and the way in which the plys and fibres move. A simple rule could be that the higher the pressure the more force is applied forcing the layers to move, and vice versa low pressure less movement. However, this may not the case as at high pressures localised thinning could occur, or even a locking effect where the plys no longer shear and move but grate and lock against each other [9]. This again will require greater understanding and optimisation for the material and effects of applied pressure.

Temperature and its distribution directly affects the materials ability to be formed as it causes a drop in viscosity which allows the composite plies to move. Therefore, the even distribution of temperature is critical to ensure uniform viscosity, and therefore motion between plies [8]. However, increased temperature results in an increased cure rate. Curing causes viscosity to increase reducing the ability to form the composite. . Therefore, a key element in this work is balancing this time frame in which the viscosity is low enough for the composite to be formed..

From the above it is clear that a balance between the 3 factors is required and additionally that this balance may need to be variable depending on the time and complexity of the process and feature being formed. For the purpose of this case study and the current phase of the project the pressure and temperature will remain constant with only the feed rate being altered.

Experimental Rig

The test rig is a simple structure there the rolling pressure is provided by two pneumatic actuators controlled by a 5 port valve and a proportional partial pressure valve that is intern controlled from a single headless controller. Heating is provided by a flexible silicone heater mat that is applied directly onto the composite and moulding tool. The feed is provided by a stepper motor controlled from a central computer that drives a leadscrew that is attached to a roller platform. The above systems are robust and easy to maintain providing a low cost and adaptable process.

In addition to the forming actuation the test rig also utilises various sensors for pressure piezo electric load washers are used and for thermal data a series of thermocouples have been applied to the test cell. In this case, however, all signals for both input and output are from a single computer. Also, the pressure and thermal signals can be made to easily run headless allowing for quick implementation of a closed loop control system.

Monitoring Method

To monitor feed rate, temperature and applied pressure during forming there are various methods that have been designed into the test cell for this project. The feed rate is perhaps the simplest process as this is derived from the number of pulses made by the stepper motor driven lead screw system; as such this is highly controlled and reliable. When considering the thermal distribution, there are both applied and resultant factors here, to ensure even heating has taken place a silicone heater matt is monitored by 6 thermocouples. The resultant temperature of the mould tool and composite surface is also monitored by 12 evenly distributed thermocouples. This method should give an even picture of the thermal heat distribution and show clearly if this is a uniform process.

Similar to the thermal distribution the applied and resultant pressure is being monitored. The applied load is measured by an embedded load cell in the roller tool; with the resultant force on the mould being measured by 4 load cells located at the corners of the mould to show the distribution of load and if there are any major imbalances that occur during the forming process.

Using the above systems, sufficient monitoring of the most important parameters can be made. The key reason for this step is to show that a forming process can be optimised and monitored without the use of additional complex material sensors and no significant changes made to the composite forming pathway.

Experiment Overview

This series of experiments aims to show how the change in feed rates used in the TRF process can affect the successful forming of acceptable components over a standard geometry at a constant applied pressure and temperature. The tables below detail the parameters used in this experiment and the variables to be evaluated.

Table 1: Summary of tests performed in this study.

Test	Temperature (°C)	Pressure (N)	Thickness (mm)	Mould Geometry	Material	Forming speed (Pulses/mS)
1	80	250	6	40MM Hump	M21 AFP	1
2	80	250	6	40MM Hump	M21 AFP	10
3	80	250	6	40MM Hump	M21 AFP	25
4	80	250	6	40MM Hump	M21 AFP	50

From Table 1 the forming parameters that will remain constant have been chosen based on previous experimental work by industrial project partners in the Aerospace industry. The temperature rated above is designed to be placed between the curing temperature and extreme limiting temperatures; this is designed to allow the composite to more easily be formed without the risk of partial or full curing taking place. Pressure, materials, thickness and moulding pattern will equally remain constant to ensure that this experiment is undertaken under controlled parameters and conditions. The samples will be transported post forming to an oven where they will be cured by an oven curing process according to the specified materials datasheet [10, 11]. Oven curing has been chosen as there is a deliberate attempt to not alter by the curing process the formation of defects within the laminate, vacuum-bagging and autoclave curing methods can have an additional effect to removing defects by further consolidation.

After the curing cycle the material samples will be physically analysed by sectioning the laminates along the length of the component at 15mm intervals, or through any obvious defects that may occur. The aim of this is to evaluate the creation of forming defects and additionally the effectiveness of the analysis system being used both based on data acquisition and evaluation and physical inspection and processing.

Anticipated production rates

We can carry out a simple calculation to work out the forming time in each case then add setup/dead time to the process and a standard 4.5hr curing cycle for the specific materials being used. If we assume that the process will take 1.5 hrs to setup, heat and start and remove the component post forming the main variable here is the time in which we take to form the composite charge. The process travels at 200 pulses per revolution and one revolution is equal to 4mm of x-axis motion with the total distance in x required 450 mm a total of 19000 pulses are required to complete this motion. We can then calculate the time in minutes to complete each run and add this to the other total time for the process of 6 hrs. These results are shown in table 2.

Table 2: Breakdown of processing times and total single unit production times.

Test	Process Time (mins)	Total time (Mins)
1	0.27	360.27
2	2.67	362.67
3	6.67	366.67
4	13.33	373.33

Case Study

As mentioned above this study is focused on the use of constant applied thermal and force properties and how the process feed rate effects the formation of the composite component. To achieve this there is are 4 tests, Table 1, with varying feed rates. The feed rate can't be reduced further in this case as holding the composite charge at elevated temperatures may lead to the resin partially curing which will lead to defects forming regardless of the forming process [8, 11].

From this testing process we can make a prediction of the potential production rates that could be achieved in an industrial process. The production rate and expected outcomes are detailed below and will be used in some part as a comparative measure to the actual testing outcomes.

Expected Outcomes

From previous studies on the forming/machining of materials it is relatively well established that as the process feed rate is increases there is a greater likely hood of a defect forming or the material undergoing changes that may lead to defect creation [12]. As such we can predict in this experiment that as we increase the feed rate there will be a higher probability of defects and or imperfections. This is largely due to the defect nucleating before the plys can slip/slide to compensate. The defect can then be exaggerated and consolidated by the roller rather than removed/smoothed by the roller [13]. In contrast the lower feed rate forming tests may face other challenges such as the nucleation of various defects that do not rapidly grow however there may be a series of defects that are hard to predict and detect, rather than the formation of one large defect. As with most processes there is also the significant demand to get a precise balancing act between an economically viable output and a product of the correct quality [14].

Results

The above experiments were carried out as described in the methodology section of the paper with no anomalous external factors affecting the process. Table 3 shows the tests and variables with a description of the forming outcomes for each example, additionally geometric data was taken across each laminate from regions of rolled and unrolled composite at 5 points across the rolled area: the start point on both the internal and external radii, the formed platform, and 5o mm after the feature as this is where we would expect defects to occur and are points of interest for quality of the forming. This data has been used to calculate a basic representation of the percentage of compaction of the laminate.

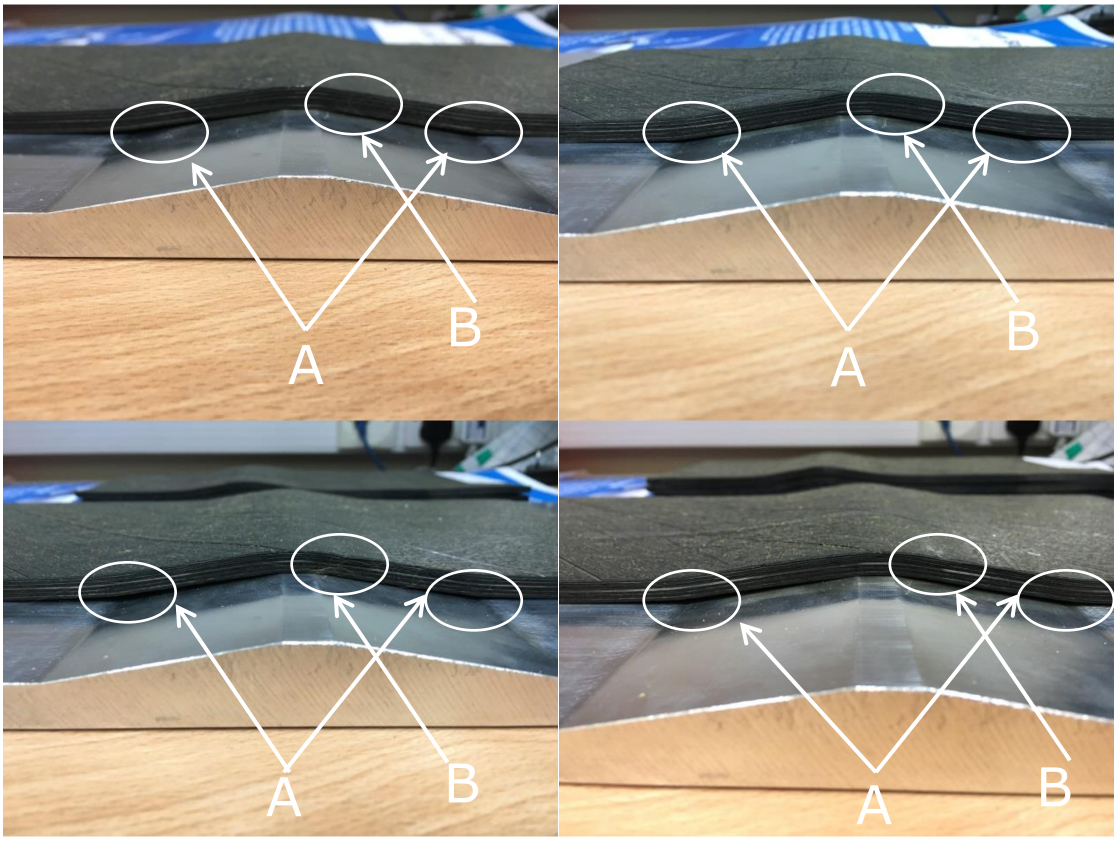

Figure 1: Post cured Laminates test 1 top left, test 2 top right, test 3 bottom left, test 4 bottom right.

Point A on all figures shows the location of the shortening of geometry and point B shows the location of the post rise potential defect location. These have proven to be repeatable and constant issues that will require further analysis and trialling.

Table 3: Table of results from case study testing.

Test	Temperature (°C)	Pressure (N)	Thickness (mm)	Forming speed (Pulses/mS)	Results and descriptions
1	80	250	6	1	Part formed with the geometry under formed on the internal radii, there is also a distinct mark that would be the expected location of a wrinkle in a thicker composite laminate. The process provided 1.16% compaction across the form.
2	80	250	6	10	Part formed with some shortening on the internal Radii as in test 1 with decreased severity; there is also a post rise dent where a wrinkle would be expected. The process provided 1.31% compaction across the form.
3	80	250	6	25	Part formed with again shortening on the internal Radii as in test 1 with decreased severity; there is also a post rise dent where a wrinkle would be expected. The process provided 1.63% compaction across the form.
4	80	250	6	50	Part formed with shortening on the internal Radii as in test 1 with decreased severity; there is also a post rise dent where a wrinkle would be expected. The process provided 1.93% compaction across the form.

Discussion

From the results above there is a link between part quality and feed rate as expected. This series of results has given us the ability to reveal the potential industrial usefulness of this technology by taking results from run 3 and 4 as acceptable. Furthermore, using the standard criteria of pressure and temperature enables us to show the rate potentials with a standard value, and future work will consider varying these parameters.

From this work we can also calculate the number of composite parts that can be produced per day, per week and per month to indicate the economy as shown in Table 4. These results are based on the assumption of a 2/3 shifts per day 24/7 production cycle. This output is also based on the output per machine/cell.

Table 4: Composite part production rates based on a 24/7 working cycle.

Test	Rate per day	Per Week	Per Month
1	3.99	27.97	111.91
2	3.97	27.79	111.17
3	3.92	27.49	109.96
4	3.85	27.00	108.00

Table 4 shows that on a daily and weekly basis the change in process feed rates doesn't yield any significant advantage. However, on a monthly basis there is a benefit of 4 components per month. When this is placed into perspective against the current leading companies in aerospace trying to achieve production rates of over 50 aircraft per month in some lines, and ever increasing back catalogues, this can be a significant advantage[15].

There is however potential to alter the part production rate and quality through further investigation. This can be combined with the greater utilisation of the in-situ monitoring technology that in this case has only been used to show that an even and constant forming process has been achieved. It will then be possible to correlate the location of defects to specific forming anomalies leading to the development of preventative that will significantly reduce defect forming for TRF.

When considering the overall process times we can also potentially make time savings in the forming phase by lowering forming temperature to reduce the time needed to heat the laminate. This is a significant area for potential improvement, however, lower temperature forming may need lower feed rates and higher pressures due to the change in viscosity of the composites materials [8,16]. This is an area for further research and may allow for significant development.

When looking at the formation of defects there appears to be a series of recurring features where dents have formed at potential defect sites just after the top of the formed ramp and external radii feature. However, these cannot be confirmed by simple visual inspection and further destructive analysis is required to better understand these faults. In the case of two of the tests the applied force data showed a rise as the tool approached the feature, and fall as it left the feature. Test 1 however, appears to have remained constant this could have been due to the speed being greater than the sensor capacity or the system not moving slow enough to react. This is expected and would need greater control to reduce. Specifically in tests 3 and 4 the force data showed a rise and fall effect around 150-250 mm in, post forming there may be evidence that the system fights the formation of a wrinkle or is fighting to keep the laminates moving continuously shown buy the gradual rise in applied force, sections will be taken of these regions and analysed for potential errors in future, this rise and fall effect is shown in figure 2.

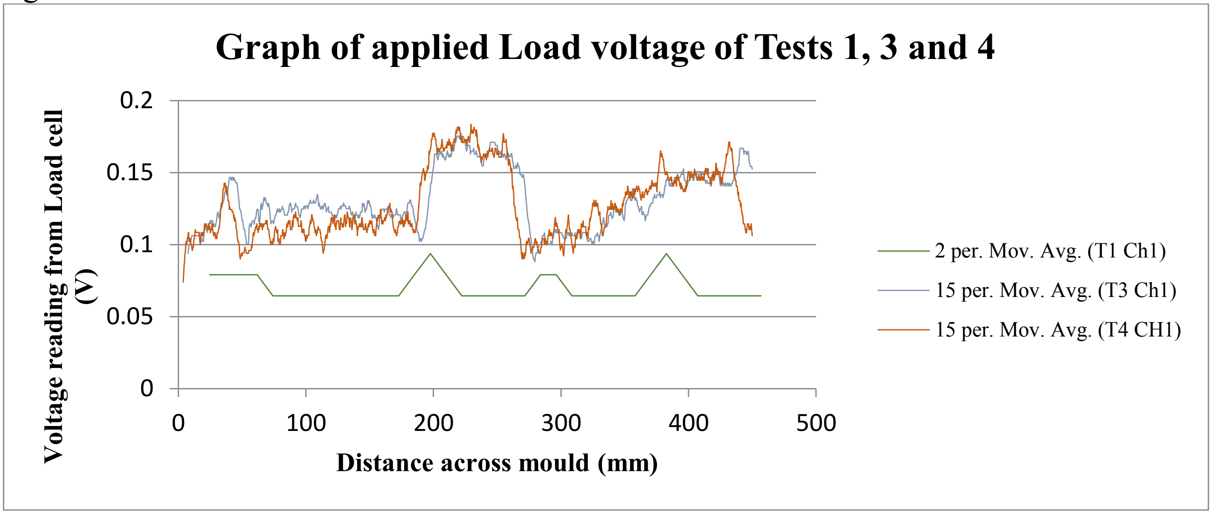

Figure 2: Graph showing applied load fluctuation of forming tests.

In all cases the tool failed to cause the material to fully acquire the desired form, but there is some evidence to suggest that at lower feed rates the tool can more easily acquire the correct form. This problem is much more complex in that there are multiple factors affecting composite forming and it maybe a combination of these that truly unlocks this technology. The variation in compaction is slight ranging from 1.16% to 1.93%, however, this does show that at slower feed rates the roller tool has greater effect on the component. Therefore, to achieve higher quality parts will require the use of slower forming feed rates.

In all cases further analysis of the data collected and of the composite panels is required, this will require the use of destructive testing and a series of comparative data analysis studies to further understand this process and how it affected the materials. However, this is outside the scope of this particular study.
There is also the potential to implement a smart controller based on data obtained from this work, where the information that has been gathered from sensors can be used as feedback.

This process will help to control the creation and size of defects with a variation of forming parameters that can be maintained at constant values unlike the current process, this will have particular advantages when considering the formation of larger and more complex geometries that may requires a degree of process variation.

Conclusions

In conclusion, this case study has indicated the potential advantage for the use of in-situ force and temperature monitoring to ensure a continuous and stable forming process that can be optimised by single and eventually multi-variable changes. Through this work we have established a range of processing speeds that achieve effective and successful forming of a composite laminate of 6 mm thickness by thermal roll forming. With a realistic picture of the current production rates that may be achieved in an industrial application. Further work will consider the variation of other relevant parameters, temperature and pressure being the most important, to improve process control and reduce defects. Using this information a smart control system may be developed to enable repeatable reliable production of parts with complex geometries and ply compositions.

References

1. Land, P., Crossley, R., Branson, D., and Ratchev, S., "Technology Review of Thermal Forming Techniques for use in Composite Component Manufacture," SAE Int. J. Mater. Manf. 9(1):2016, doi:10.4271/2015-01-2610.
2. Everton, S,K. Hirsch, M. Stravroulakis, P. Leach, R.K. Clare, A.T. Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing, Materials & Design, Volume 95, 5 April 2016, Pages 431-445, ISSN 0264-1275, http://dx.doi.org/10.1016/j.matdes.2016.01.099.
3. S. Erland, T.J. Dodwell, R. Butler, Characterisation of inter-ply shear in uncured carbon fibre prepreg, Composites Part A: Applied Science and Manufacturing, Volume 77, October 2015, Pages 210-218, ISSN 1359-835X, http://dx.doi.org/10.1016/j.compositesa.2015.07.008.
4. Nezami, F.N. Gereke, T. Cherif, C. Analyses of interaction mechanisms during forming of multilayer carbon woven fabrics for composite applications, Composites Part A: Applied Science and Manufacturing, Volume 84, May 2016, Pages 406-416, ISSN 1359-835X, http://dx.doi.org/10.1016/j.compositesa.2016.02.023.
5. R. Akkerman and S.P. Haanappel, 6 - Thermoplastic composites manufacturing by thermoforming, In Advances in Composites Manufacturing and Process Design, edited by Philippe Boisse,, Woodhead Publishing, 2015, Pages 111-129, ISBN 9781782423072, http://dx.doi.org/10.1016/B978-1-78242-307-2.00006-3.
6. Syed Ali Ashter, 2 - The Thermoforming Process, In Thermoforming of Single and Multilayer Laminates, William Andrew Publishing, Oxford, 2014, Pages 13-38, ISBN 9781455731725, http://dx.doi.org/10.1016/B978-1-4557-3172-5.00002-5.
7. James L. Throne, Understanding Thermoforming, In Understanding Thermoforming (Second Edition), Hanser, 2008, Pages I, III-IV, VI-XIII, ISBN 9783446407961, http://dx.doi.org/10.3139/9783446418554.fm.
8. D.C. Blest, B.R. Duffy, S. McKee, A.K. Zulkifle, Curing simulation of thermoset composites, Composites Part A: Applied Science and Manufacturing, Volume 30, Issue 11, November 1999, Pages 1289-1309, ISSN 1359-835X, http://dx.doi.org/10.1016/S1359-835X(99)00032-9.
9. Lebrun, G. et al. 2016. Influence of Consolidation and forming parameters in the molding od continues fibre reinforced thermoplastic composites. Available at: http://speautomotive.com/SPEA_CD/SPEA2002/pdf/b02.pdf Accessed: 01/06/2016
10. Hexcel. 2016. Hexply M21. Available at: http://www.hexcel.com/Resources/DataSheets/Prepreg-Data-Sheets/M21_global.pdf Accessed: 01/06/2016
11. Crane, L. W., et al. (1973). "Analysis of curing kinetics in polymer composites." Journal of Polymer Science: Polymer Letters Edition 11(8): 533-540.
12. Youngsik Choi, Influence of feed rate on surface integrity and fatigue performance of machined surfaces, International Journal of Fatigue, Volume 78, September 2015, Pages 46-52, ISSN 0142-1123, http://dx.doi.org/10.1016/j.ijfatigue.2015.03.028.
13. P. Hallander, J. Sjölander, M. Åkermo, Forming induced wrinkling of composite laminates with mixed ply material properties; an experimental study, Composites Part A: Applied Science and Manufacturing, Volume 78, November 2015, Pages 234-245, ISSN 1359-835X, http://dx.doi.org/10.1016/j.compositesa.2015.08.025.
14. MIT. 2016. Quality and Quantity Modeling of a Production Line. Available at: http://dspace.mit.edu/bitstream/handle/1721.1/3918/IMST022.pdf Accessed: 01/06/2016
15. Aviation week network. 2015. Production Rates: Are Airbus And Boeing Aiming Too High? Available at: http://aviationweek.com/paris-air-show-2015/production-rates-are-airbus-and-boeing-aiming-too-high Accessed: 01/06/2016
16. CompositesWorld. 2006. Thermoformable Composite Panels, Part 1. Available at: http://www.compositesworld.com/articles/thermoformable-composite-panels-part-1 Accessed: 01/06/2016