DEFECTS FORMATION IN AUTOMATED FIBER PLACEMENT TECHNOLOGY

Sara Srebrenkoska[1*], Vladimir Dukovski[2]

[1] Faculty of Mechanical Engineering, University Goce Delcev Stip, North Macedonia
[2] Faculty of Mechanical Engineering, Ss Cyril and Methodius, Skopje, North Macedonia
[*] e-mail:sara.srebrenkoska@ugd.edu.mk

Scientific paper
UDC: 677.1/.5+621.7
DOI: 10.5937/tekstind2204022S

Abstract: *In the frame of this work, a robotic Automated fiber placement - AFP in situ process was applied to obtain high quality thermoplastic composite structures. Automated fiber placement (AFP) with laser assisted heating (LAFP) is an attractive manufacturing technology for the development of lightweight and high performance components, primarily for the aerospace, automotive, military and many other dominant industries worldwide. For the samples laminate plates produced with the AFP procedure, the flexural strength was investigated, and optical images were analyzed for irregularities such as pore content and weaker interlaminar bonding between the layers.*

Keywords: automated fiber placement, thermoplastic, laser, flexural strength, irregularities.

FORMIRANJE DEFEKATA U TEHNOLOGIJI AUTOMATSKOG POSTAVLJANJA VLAKANA

Apstrakt: *U okviru ovog rada primenjen je robotizovani proces automatizovanog postavljanja vlakana - AFP in situ za dobijanje visokokvalitetnih termoplastičnih kompozitnih struktura. Automatsko postavljanje vlakana (AFP) sa laserskim grejanjem (LAFP) je atraktivna proizvodna tehnologija za razvoj lakih komponenti visokih performansi, prvenstveno za vazduhoplovnu, automobilsku, vojnu i mnoge druge dominantne industrije širom sveta. Za uzorke laminatnih ploča proizvedenih AFP postupkom, ispitivana je čvrstoća na savijanje, a optičke slike su analizirane na nepravilnosti kao što su sadržaj pora i slabija interlaminarna veza između slojeva.*

Ključne reči: automatizovano postavljanje vlakana, termoplast, laser, čvrstoća na savijanje, nepravilnosti.

1. INTRODUCTION

Current trends in composite manufacturing technologies for the aerospace industry are focussed on the automatic deposition of composite tapes and new multi-component materials systems, such as toughened prepregs, for improved component performance, damage tolerance or added functionality. The automation and material technologies enabling these advances have progressed much further than the capability to understand, predict, and optimise the manufacturing processes [1], [2]. Two of the main technologies for automated deposition of pre-preg material are Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) [3], [4], [5]. In recent years there have been a number of experimental and numerical studies carried out to predict and characterise the knockdown effect of gaps and overlaps on final mechanical properties of components manufactured by AFP.

2. AUTOMATED FIBER PLACEMENT (AFP)

Automated Fibre Placement (AFP) is a fiber/tape laying processes for production of high performance composite laminates from unidirectional prepreg materials. AFP is a main technology used today to produce complex composite parts [6].

The term fiber placement is used to describe the process of laying a group of multiple narrow prepreg strips on more complex surfaces. The production process with automated laying of thin prepreg strips with an accurate width of up to 12.7 mm or using single fibers or multiple fibers forming narrow strips (tow) with widths of 3.175 mm, 6.35 mm or 12, 7 mm (0.125 inch, 0.250 inch or 0.50 inch) is known as AFP technology. With the AFP technology, fibers can be lay up in different orientations. AFP machines are usually equipped with a head that can carry up to 32 spools of material to be laid (Fig.1) .

During the process, each prepreg strip is pulled from a separate spool which is housed in a tensioning system. Each individual strip is then pulled to the lay-up head via a conveyor system. At the end of the head, through which the composite material is laid, each individual strip is grouped into an output wide strip, the so called course, whose width can vary during the process. During application, each individual prepreg tape moves at a certain speed, which allows the tape to be laid freely on a complex shaped surface[7-9].

For the AFP process, the thermoplastic fibers/tapes that are lay up should be heated, and the heat source can be an infrared heater, hot air or a laser. So, through their heating, the layers that are being laid stick together and to achieve consolidation, a compaction roller is used. In this procedure, a robot is most often used to lay the strips along predefined paths which allows a high degree of freedom in the design of the final product [10-12].

The research that has been done on the application of the robot in the automation of the processes for the production of composite products is aimed at improving the existing production processes [13,14].

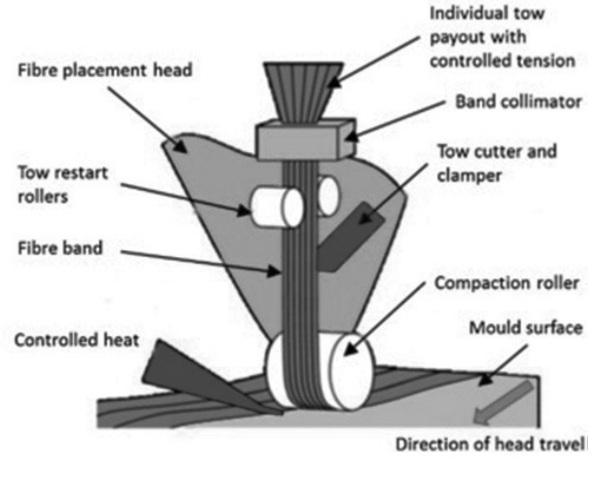


Figure 1. Automated fibre placement head, redrawn from [10]

Most of the research on automated production is oriented towards the application of thermoplastic prepreg materials, although many responsive and load-bearing composite parts obtained with thermoset materials are in use today [15-18]. The reason for such research is that during the processing of thermoplastic prepreg, the material can be combined in situ directly during laying. However, when processing thermoplastic prepreg as well as when processing thermoset prepreg, many challenging problems appear such as: the appearance of gaps (gaps) and overlaps (overlap) between the strips, which affects the final characteristics of the material, which requires in-depth research. From the research that is being done on the application of robotic processes for the automatic laying of fibers/strips, it is expected to ensure better obtaining of high quality structures from composite materials with a new process called in situ consolidation [19-21].

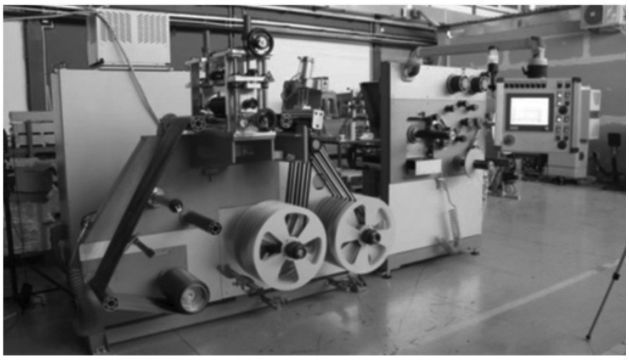
3. EXPERIMENTAL

In the frame of this investigation, thermoplastic unidirectional prepregs (UD) were used for the production of samples - laminate plates from thermoplastic composite materials.

The UD prepreg material (Toho Tenax, Germany) is based on carbon fiber (Tenax®-E HTS45 12K) and polyether ether ketone PEEK. The PEEK thermoplastic polymer matrix offers excellent chemical and solvent resistance. The carbon fibers Tenax®-E HTS45 have high tensile strength and they are prepared with surface treatment for thermoplastic applications. Their combination with PEEK result in a prepreg material that is good for obtaining superior composite materials. characteristics.

UD prepreg tape with 304.8 mm wide is slitted into 6.35 mm wide strips on a slitting and rewinding machine manufactured by Microsam (Prilep, Nort Macedonia). In figure 2 the machine for sliting the prepreg is given, where 48 strips of prepreg are obtained from its width. The laying of the tapes was done using an AFP head for laying prepreg tape, manufactured by Microsam (Prilep, Nort Macedonia), which is mounted on a robotic arm.

The robotic arm with the AFP head which was applied for the lay up of the UD prepreg tapes is presented on figure 3. The AFP head has 4 spools of 6.35 mm wide prepreg strips and during the lay up these 4 prepreg strips are forming one course with 25.4 mm wide. Six courses like that create one layer or one lamina. The laminate samples were produced with 16 layers laid at an angle of 0°, so that the thickness of the resulting laminate plates is ~ 2 mm. The obtained laminate plates have dimensions: (300 x 150) mm. So, for one layer 6 courses or 24 strips of prepreg are applied. The construction of one lamina or one layer is shown in figure 4.



©Mikrosam
Figure 2. Prepreg slitting and rewinding machine, manufactured by Mikrosam

©Mikrosam
Figure 3. Robotic arm with AFP head with 4 spools at the Institute for Advanced Composites and Robotics (manufactured by Mikrosam – Prilep)

Table 1 shows the conditions under which the prepreg strips were lay up using the AFP procedure.

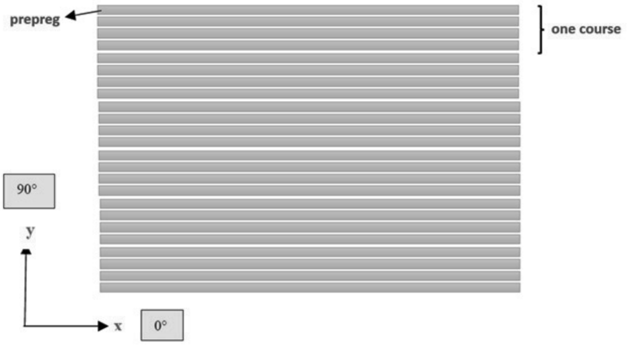


Figure 4. Construction of one lamina laid by AFP procedure

3. RESULT AND DISCUSSION

In the frame of this investigatio, four samples - laminate plates were produced from UD prepreg with the AFP procedure. When multiple prepreg are lay up simultaneously forming a course there is a possibility of irregularities such as gaps and overlaps and there is no continuity in the width of the course [18,19]. It results in defects in the microstructure and in obtaining lower values for stress during bending of the samples [20-22].

Namely, applying a higher processing temperature and higher pressure when the laser beams fall at a smaller or larger angle results in formation of a good bond between the layers. Samples obtained at lower pressure and higher processing temperature as well as those obtained at lower temperature and higher pressure showed lower values for bending stress (table 2). Those samples also have a higher percentage of pores, which is clearly visible from the obtained metallographic images from the optical microscope.

The metallographic images of the cross-sections of samples 1 and 4 are given on figure 5. From the optical microscope images and the calculated

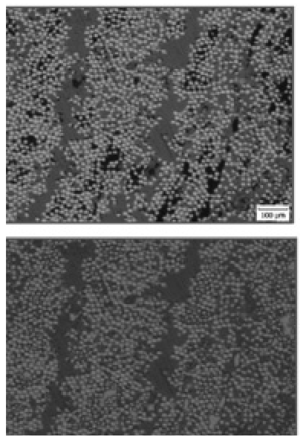
Table 1. Conditions for lay up using the AFP procedure

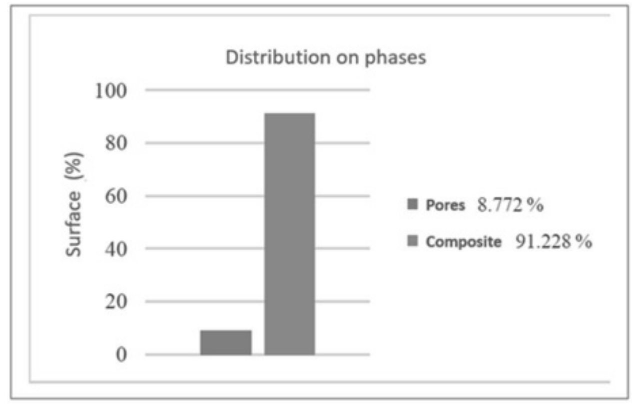
LAFP-UD	Processing temperature, °C	Laser angle, °	Roller pressure, N
1	480	25	530
2	480	22	530
3	480	25	385
4	420	22	530

Table 2. Results obtained for bending stress for LAFP-UD specimens

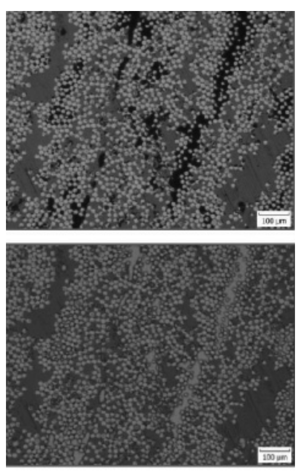
Marking of samples LAFP-UD		Width *b* (mm)	Thickness *d* (mm)	*F* (N)	σ (MPa)	σ_{sr} (MPa)
1	1-1	15,20	1,95	1267,1	1150,95	1016,53
	1-2	15,91	1,93	1058,5	938,29	
T= 480⁰C	1-3	16,01	2,07	1219,8	934,09	
P=530N	1-4	15,80	2,00	1200,4	997,17	
$a = 25^0$	1-5	15,94	1,99	1277,1	1062,16	
2	2-1	15,75	2,11	1238,8	927,50	905,45
	2-2	15,80	2,08	1037,3	796,67	
T= 480⁰C	2-3	16,01	2,05	1097,9	856,69	
P=530N	2-4	16,05	2,08	1331,1	1006,39	
$a = 22^0$	2-5	15,75	2,11	1255,5	940,01	
3	3-1	15,49	1,60	713,9	945,16	864,93
	3-2	16,40	1,49	655,5	945,18	
T= 48⁰C	3-3	15,49	1,60	631,2	835,67	
P=385N	3-4	15,10	1,53	574,3	858,67	
$a = 25^0$	3-5	15,60	1,66	605,9	739,98	
4	4-1	15,15	1,87	893,9	885,83	807,27
	4-2	15,50	1,79	739,1	781,31	
T= 420⁰C	4-3	15,20	1,89	932,8	901,95	
P=530N	4-4	15,15	1,70	690,5	827,97	
$a = 22^0$	4-5	14,89	1,70	524,0	639,29	

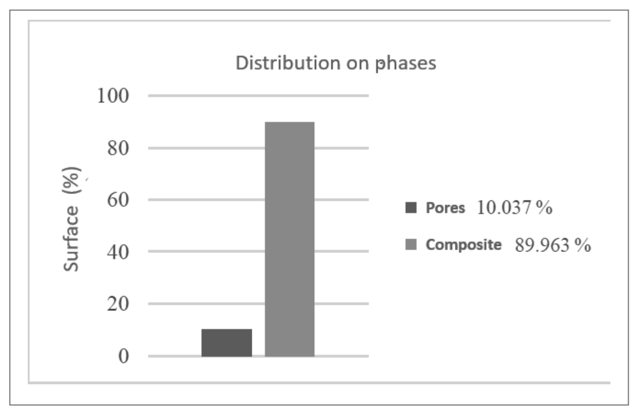
percentage of pores, it can be noticed that the laminate samples obtained with the AFP procedure have a high percentage of pores. Samples obtained at a higher processing temperature and higher roller pressure showed a pore content of about 8%, while samples obtained at a lower processing temperature and higher roller pressure and opposite showed a pore content of about 10%.





a) LAFP UD sample 2





b) LAFP UD sample 4

Figure 5. Metallographic images of a cross-section of samples of laminate plates with the label LAFP-UD a) sample 2; b) sample 4

It clearly shows that the AFP process results in laminate plates with weaker characteristics due to the appearance of irregularities during the formation of the courses of the four narrow prepreg that laying up simultaneously on a flat surface.

4. CONCLUSION

The AFP process can be successfully used for lay up of thin prepreg strips on surfaces that can be curved, namely, to obtain asymmetric laminates. When applying this process for laying prepreg tapes on such asymmetric surfaces, it is possible to change the physical orientation of the tapes locally, which results the overlapping of gaps and the reduction of defects inside the structure. Therefore, this process is mostly applied to obtain smaller and curved parts, and when laying on flat surfaces, the accuracy of the robot becomes a key issue when applyed to laying prepreg tapes.

In this research the pore content is from 8% to 10% which clearly shows that the accuracy of the robot has an important role. On the other hand the AFP process is a technology that is applied to lay up prepreg tapes on surfaces that can be curved and which can rotate, as well as for obtaining smaller composite parts.

REFERENCES

[1] Zobeiry N., Forghani A., Li, C., Gordnian K., Thorpe R., Vaziri R., et al. (2016). *Multiscale characterization and representation of composite materials during processing* Philosophical Transact Royal Soc London A: Mathemat, Phys Eng Sci, 374, 2071.

[2] Baran I., Cinar K., Ersoy N., Akkerman R., Hattel.J. (2017). Hattel. *A review on the mechanical modeling of composite manufacturing processes,* Archiv Computat Methods Eng 24, 365–395, https://doi.org/10.1007/s11831-016-9167-2

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

https://doi.org/10.1016/j.compositesb.2011.12.003

[4] Grimshaw M.N., Grant C.G., Luna Diaz JM. (2001). Advanced Technology Tape Laying for Affordable Manufacturing of Large Composite Structures.

[5] Marsh, G. (2011). *Automating aerospace composites production with fibre placement,* Reinf Plast, 55 (3) 32-37.

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

https://doi.org/10.1016/j.compositesb.2011.12.003

[7] Comer A.J., Ray, D., Obande, W.O., Jones D., Lyons, J., Rosca I., et al. (2015). *Mechanical characterisation of carbon fibre-PEEK manufactured by laser- assisted automated-tape-placement and autoclave,* Compos Part A Appl Sci Manuf, 69, 10-20, 10.1016/j.compositesa.2014.10.003.

[8] Di Francesco M., Veldenz, L., Koutsomitopoulou, A., Dell'Anno, G., Potter K. (2015). *On the development of multi-material automated fibre placement technology.* Int. Conf. Manuf. Adv. Compos., Bristol, UK.

[9] Lukaszewicz, D.H.J.A., Potter K.D., Eales J. (2013). *A concept for the in situ consolidation of thermoset matrix prepreg during automated lay-up,* Compos Part B Eng, 45, 538-543, 10.1016/j.compositesb.2012.09.008.

[10] Debout P., Chanal, H., Duc, E. (2011). *Tool path smoothing of a redundant machine: application to automated fiber placement,* CAD Comput Aided Design, 43 (2),122-132.

[11] Veldenz L., Di Francesco, M., Astwood, S., Dell'Anno, G., Kim, B.C., Potter K. (2016). *Characteristics and processability of bindered dry fibre material for automated fibre placement,* 17th Eur. Conf. Compos. Mater., Munich, DE.

[12] Grouve, W.J.B., Warnet, L.L., Rietman, B., Akkerman, R. (2012). *On the weld strength of in situ tape placed reinforcements on weave reinforced structures,* Compos Part A Appl Sci Manuf, 43 (9), 1530-1536, 10.1016/j.compositesa.2012.04.010.

[13] Comer A.J., Ray D., Hammond P., Lyons J., Obande W.O., Jones D. (2014). *Wedge Peel interlaminar toughness of carbon-fibre/PEEK thermoplastic laminates manufactured by Laser Assisted Automated Tape Placement (LATP)* SAMPE Eur. - SETEC, Tampere, FI.

[14] Matveev M.Y., Schubel P.J., Long A.C., Jones I. A (2016). *Understanding the buckling behaviour of steered tows in Automated Dry Fibre Placement (ADFP)* Compos Part A Appl Sci Manuf, 90, 451-456, 10.1016/j.compositesa.2016.08.014.

[15] Khan M.A., Mitschang P., Schledjewski R. (2013). *Parametric study on processing parameters and resulting part quality through thermoplastic tape placement process,* J. Compos. Mater., 47 (4), 485-499, 10.1177/0021998312441810Feb.

[16] Nagelsmith, M., Guerrits, W. (2013). Influence of steering radius on the mechanical properties of fiber placed composite laminates. In ICCS17-17th International Conference on Composite Structures Porto, Portugal.

[17] Oromiehie E., Prusty B.G., Compston P., Rajan G. (2017). *The influence of consolidation force on the performance of AFP manufactured laminates,* Proceedings of the ICCM International Conferences on Composite Materials, Faculty of Engineering and Information Sciences - Papers: Part B. 1810. Online]. Available:https://ro.uow.edu.au/eispapers1/1810

[18] Croft K., Lessard L., Pasini D., Hojjati M., Chen, A.J. (2011). Yousefpour. *Experimental study of the effect of automated fiber placement induced defects on performance of composite laminates* Compos, Part A Appl. Sci. Manuf., 42 (5),484-491, 10.1016/j.compositesa.2011.01.007 May.

[19] Rafal A., et al. (2019). *An experimental investigation concerning the effects of AFP defects on progressive failure of tensile coupons,* AIAA SciTech Forum 1-9, 10.2514/6.2019-1547.

[20] Harik R., Gurdal Z., Saidy C., Williams S.J., and Grimsley*m B. (2018). Automated fiber placement defect identity cards: cause, anticipation, existence, significance, and progression,* Accessed: Mar. 25, 2020. [Online]. Available: https://www.researchgate.net/publication/326464139

[21] Denkena, B., Schmidt, K.,Völtzer, K., Hocke, T. (2016). *Thermographic online monitoring system for automated fiber placement processes,* Compos. Part B Eng., 97, 239-243, 10.1016/j.compositesb.2016.04.076 Jul.

[22] Shirinzadeh B., Foong C.W.,Tan B.H. (2000). *Robotic fibre placement process planning and control,* Assembly Autom 20, 313–320.

Primljeno/Received on: 25.10.2022.
Revidirano/ Revised on: 27.11.2022.
Prihvaćeno/Accepted on: 29.11.2022.