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Robotized Automated Fiber Placement and Automated Tape Laying (AFP/ATL) processes for composite material part production

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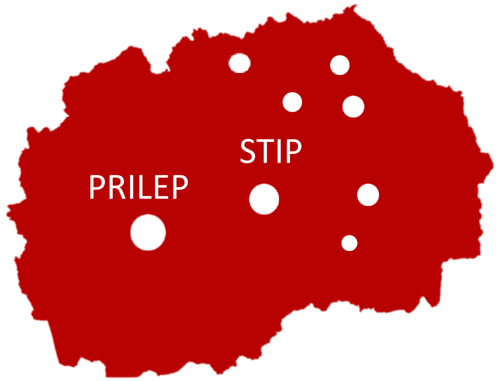

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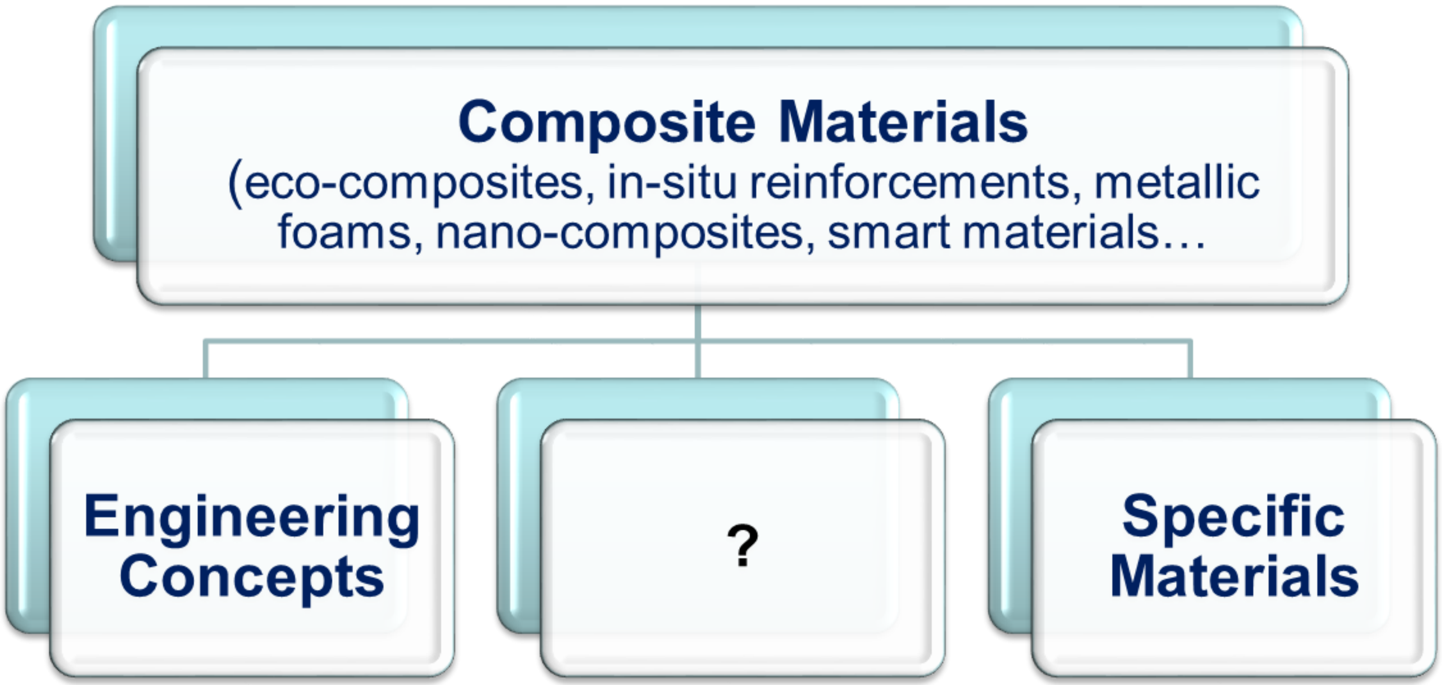


Based to the end use requirements for the composite materials since the most important is that we can interfere with their structure and tailor their properties.

APPLICATION

Polymer composite materials

- High performance materials made from fibre reinforced polymer (FRP)
- They are ideal materials for structural applications where high strength-to-weight and stiffness-to-weight ratios are required.
- Requirements are multiple and of different kind i.e. they are multidisciplinary and comprise different branches of science: mechanics, chemistry, physics, strength of materials.

Polymer composite materials

Polymer composite material: two phased material. It is composed of reinforcement and matrix which are bonded at interface.
*The reinforcing material provides FRP composite with **strength and stiffness** and **matrix** material which is **continuous phase** gives **rigidity and environmental protection**.*

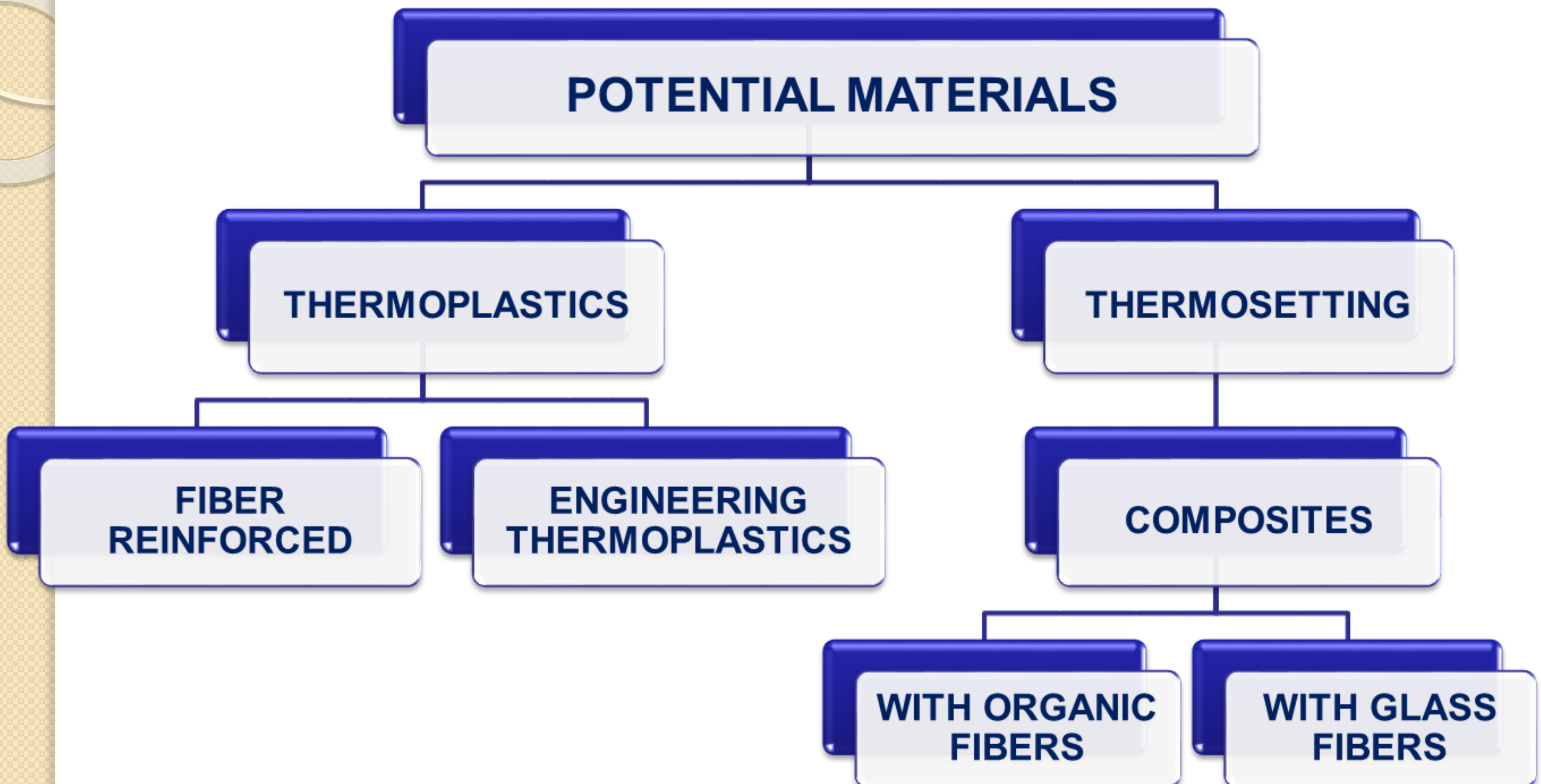
Thermoplastic polymers:

- ✓ *Can be reformed and reshaped by simply cooling and heating,*
- ✓ *flexible and reformable,*
- ✓ *Have lower stiffness and strength*
- ✓ *poor creep resistance at high temperature, and*
- ✓ *Are more susceptible to solvents*

Thermosetting polymers:

- ✓ *Cannot be remelted and reformed.*
- ✓ *Offer high rigidity, thermal and dimensional stability, high electrical, chemical and solvent resistance.*

Polymer composite materials



Engineering plastics are used "as they are" with no possibility to interfere with their structure i.e. their properties. In fact, all these are commercial products.

Polymer composite materials

- **Research and development -** have grown rapidly
- fibers and matrix materials,
- fabrication process.

- **Advantages over other traditional materials:**
- high strength to weight ratio,
- ability to be molded in various shapes,
- potential resistance to environmental conditions, resulting in potentially low maintenance cost.

- **Application:**
- upgrading existing structures and
- building new ones which can be applied to various types of structures, for example: platforms, buildings, bridges and etc.

Raw materials

Thermosetting resins

- *Epoxy resin for laminating*
- *Epoxy resin for filament winding*
- *Phenolic resin*
- *Vinyl ester*
- *Polyester resin for pultrusion process*

Accelerator for resins

Hardener for resins

Thermoplastic resins

- ***Isostatic Polypropylene (PP)***
- ***Poly lactic acid (PLA)***
- *Polyvinyl butyral (PVB)*
- *Polycarbonate (PC)*
- *Polyethylene (PE)*
- *Nylon*

Raw materials

Fabrics used for laminating

- *Glass, Aramid, Carbon fabric*
- *Woven roving fabric*
- *Cotton fabric*
- *Nonwoven (mat) material*

Rovings used for filament winding

- *Glass*
- *Carbon*
- *Polyester*
- *Aramid*

Natural fibers/fillers

- *Kenaf*
- *Cotton*
- *Rice hulls*
- *Paper*

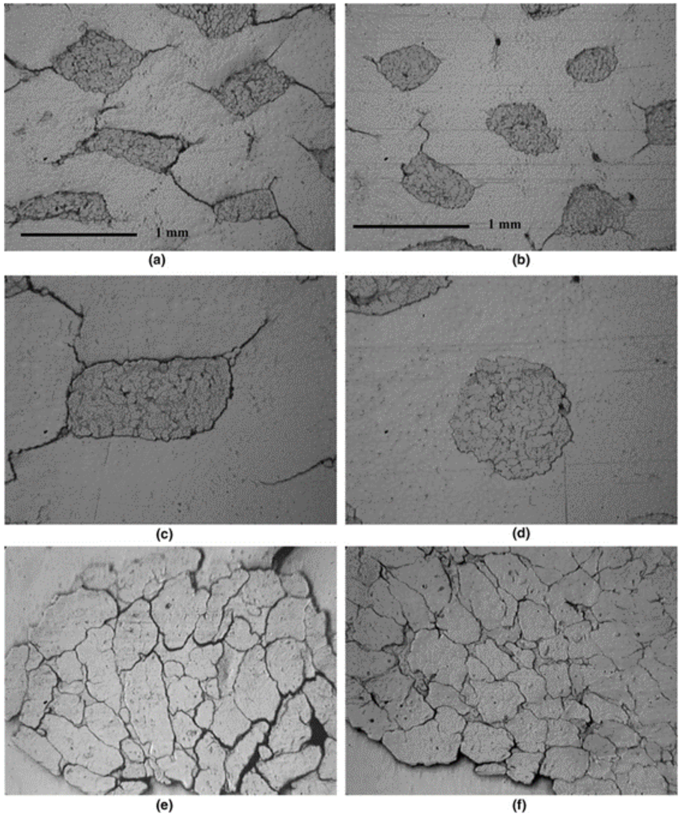
Interface

Interface is there the fibers and matrix materials are chemically and physically bonded together.

Approaches to enhance fiber/matrix adhesion strength:

- polymer matrix modification
  (by using compatibilizing agent (CA))
- fiber (surface) modification
- polymer and fiber modification
- processing conditions/new technologies

Fiber/matrix interface region- key factor determining the load transfer



Technology for composite production

- Impregnation – applicable to fabrics only
- Laminating (molding) –applicable to prepregs only
- Automate Fiber Placement (AFP)
- Automate Tape Laying (ATL)
- Filament winding –applicable to rovings only
- Structural Reaction Injection Molding (SRIM)
- Reinforced Reaction Injection Molding (RRIM)
- Compression molding – open and close mold
- Reactive blending
- Pultrusion

Manufacturing Techniques

Lay-up

Hand lay-up / Wet lay-up, Spray lay-up, Prepreg Lay-Up

Automatic Fiber Placement - Automatic Tape Layup

Compression molding

Resin injection molding

High-pressure compression molding

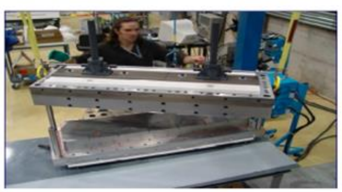
Injection molding

Filament winding

Helical winding, Hoop winding

Autoclave molding

Prepregs: an assembly of reinforcement impregnated with resin, prepared for preforming into a composite shape before the curing process used to set the resin.



Molding Compounds

SMC (Sheet molding compound)

BMC (Bulk molding compound)

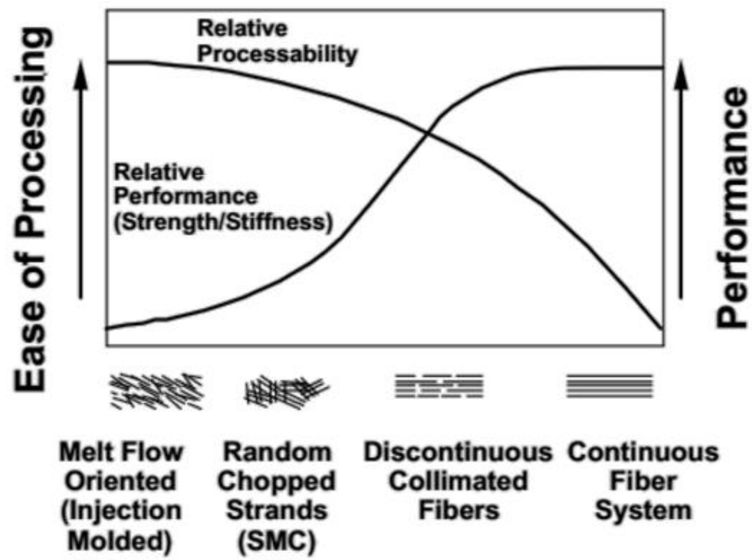
Resin transfer molding (RTM)

Flexible RTM (FRTM)

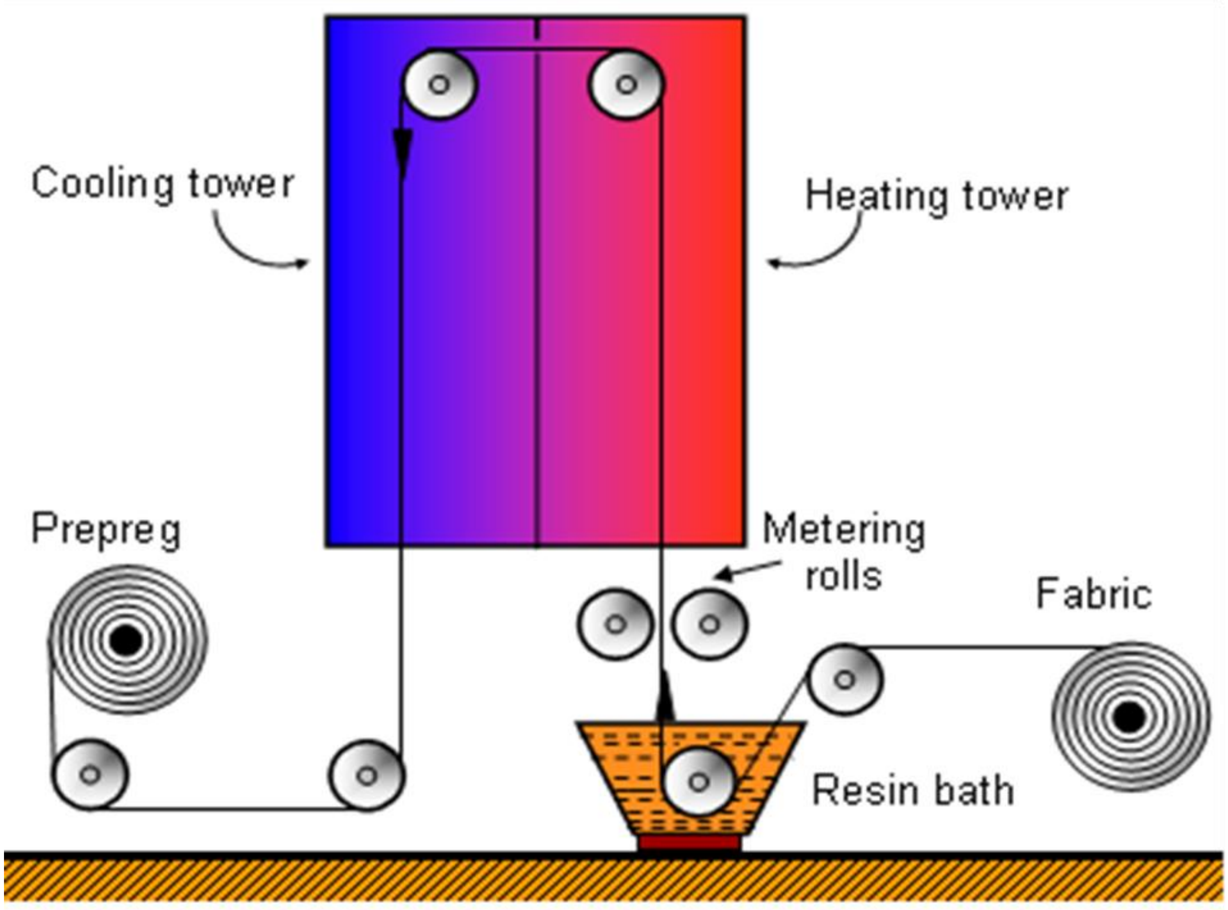
Compression RTM (CRTM)

Vacuum assisted RTM (VARTM)

High-speed RTM (HSRTM)

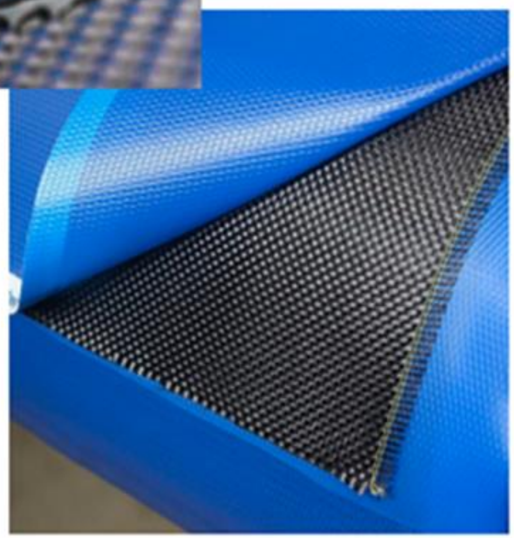


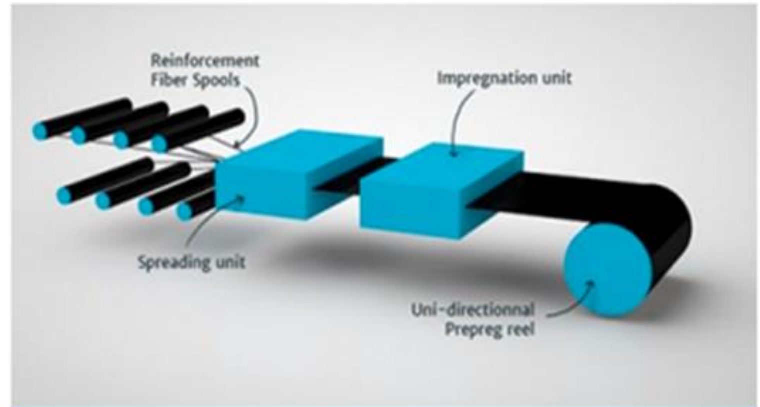
Impregnation process



The end product is prepreg (pre-impregnated fabric with resin) which is considered a semi-finished product.

Composite Precursor: Prepreg/Tow-preg





Prepreg

- Pre-impregnated fiber materials are called as prepregs.
- Prepregs have a higher fiber content of 65%.
- They are available in both cloth or tape form.
- Usually, woven cloths are pre-impregnated, but woven rovings and chopped strand mats are also pre-impregnated.

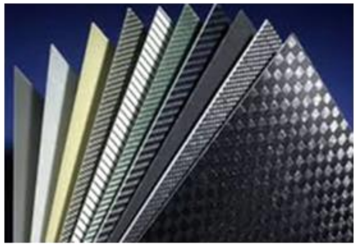
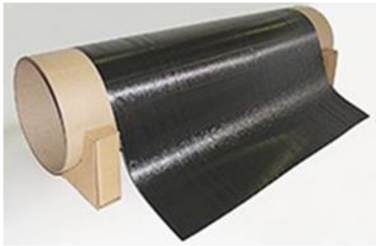
Characteristics of good prepreg:

- The fiber to resin ratio should be high and should not vary from place to place.
- Volatile contents and solvents should be minimum.
- The prepreg should be flexible and tack free.
- The material should have long storage life.
- During molding, the resin should be soften and flowable, filling the mold cavity without voids and defects.

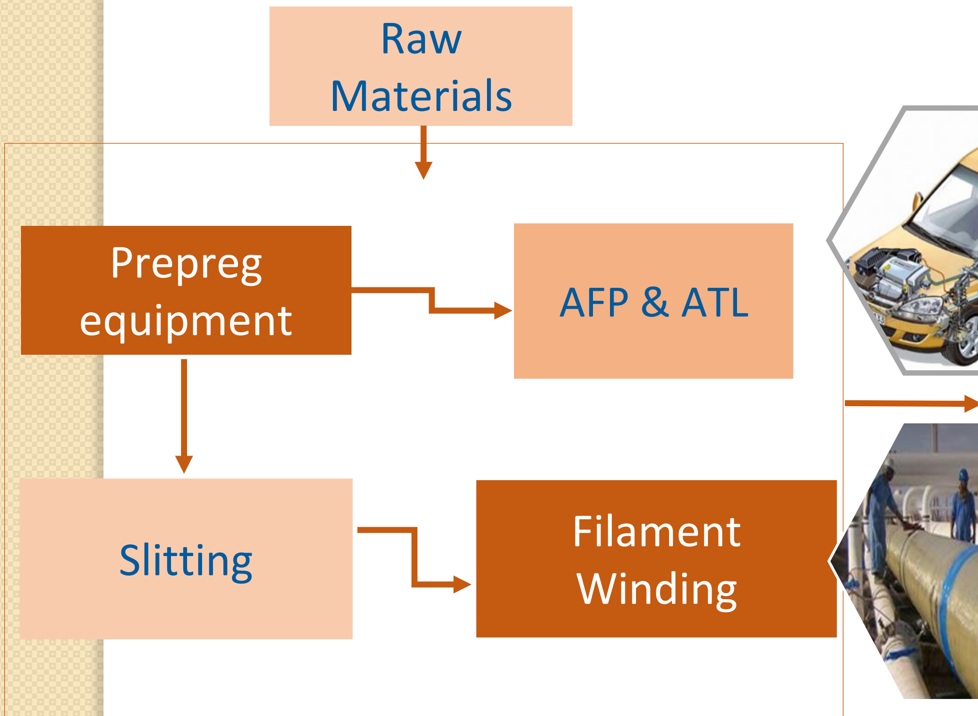
Materials

- Carbon fiber is the most commonly used as reinforcing material, but other fibers like glass fiber, boron have also been used.
- Epoxy and polyester resins are used as the impregnating agents.



Manufacturing Advance Polymer Composites by using prepreg or tow-preg



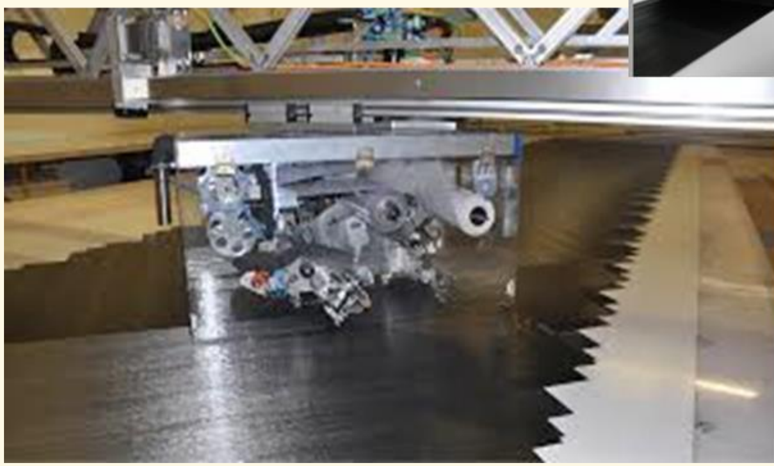
new advanced composite materials
novel products

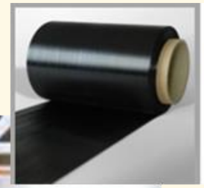
crash-resistant structures, aircraft structures fuel tanks for hydrogen storage etc.

- Vacuum molding
- Compression molding
  (open and closed mold)
  end product = COMPOSITE LAMINATE
- Filament winding– is used for rowing
  end product = COMPOSITE PIPE
- **Automated production processes – AFP/ATL technologies**

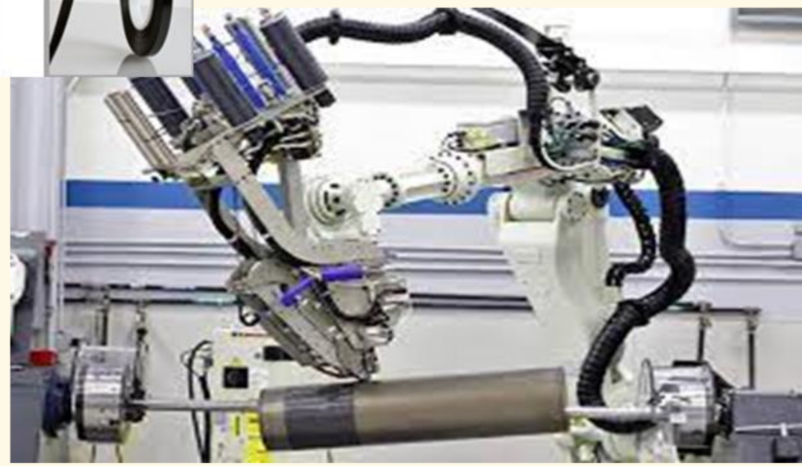
Automated Fiber Placement – **AFP** and Automated Tape Laying – **ATL** technologies

ATL





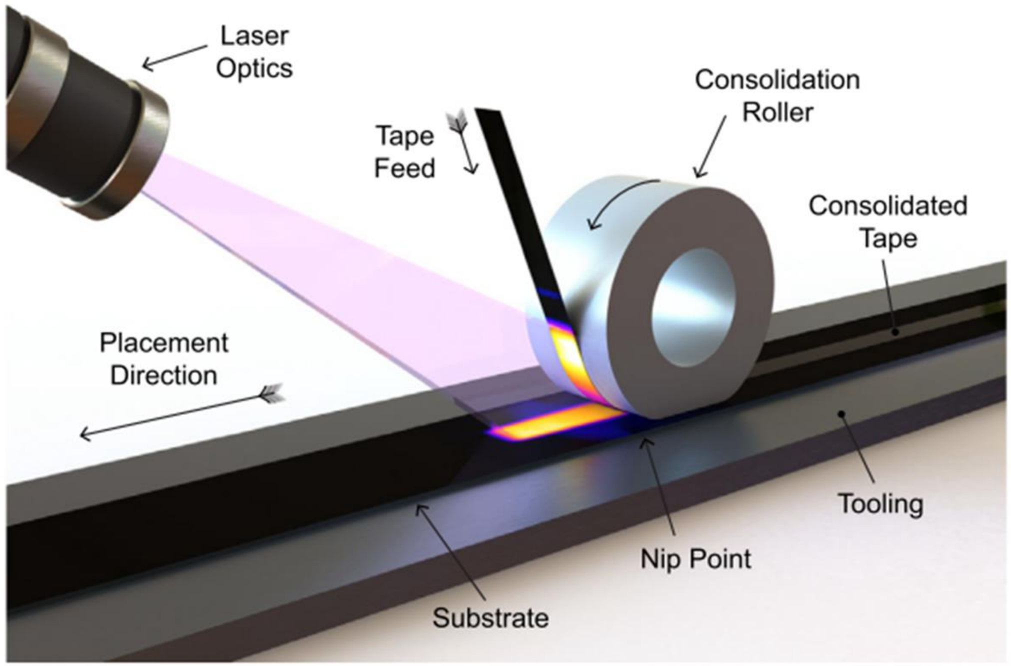
AFP



- new production technologies
- are still being researched and improved
- promising technology for fabrication of advance aerostructures and structures for automotive and other industries

✓ potential for in situ consolidation
✓ flexible and automated production
✓ high productivity and
✓ low energy consumption

In Situ placement process

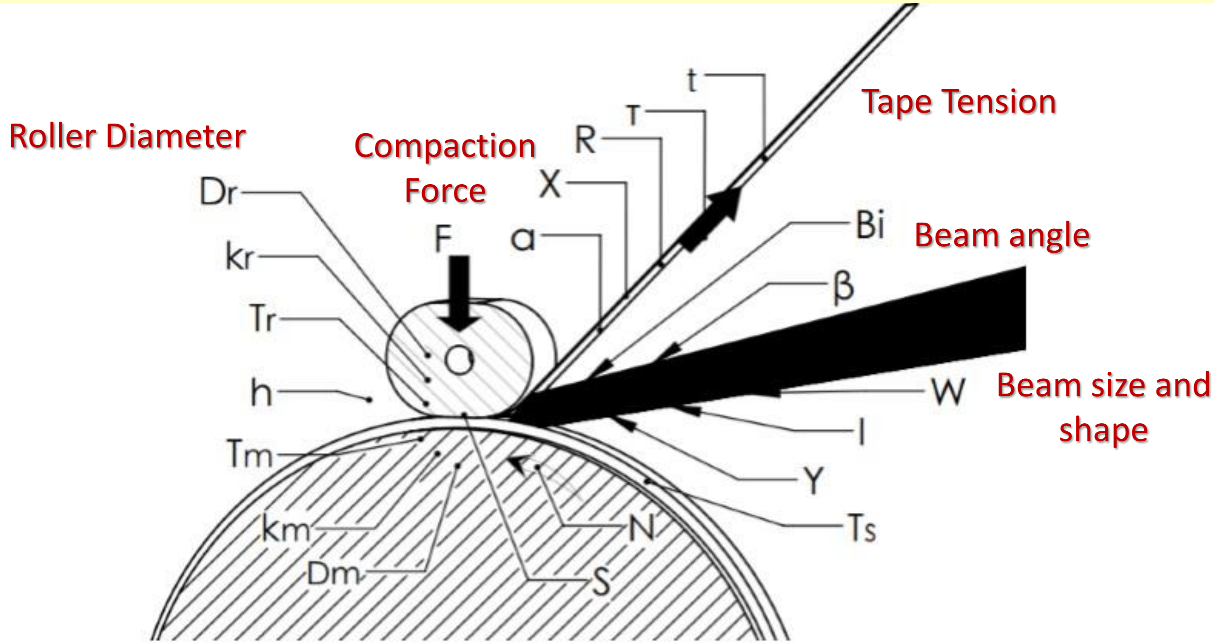


The concept of in-situ consolidation is simple:

- robot with AFP/ATL head – tape placement
- control software - an important part of the whole system (robot motion, tape laying speed, compaction force, heat source temperature etc.)
- laser application - heating
- compaction roller - consolidation

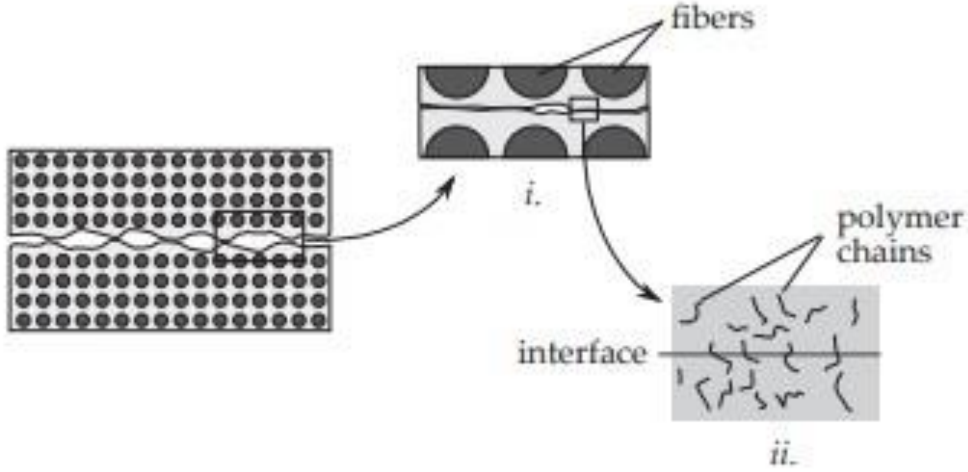
Incoming impregnated tape once at contact with the substrate under sufficient pressure and temperature above melting point, consolidates and crystallizes upon cooling at either controlled (heated mandrel) or uncontrolled rate.

Parameters involved in the Laser Heating Placement Process

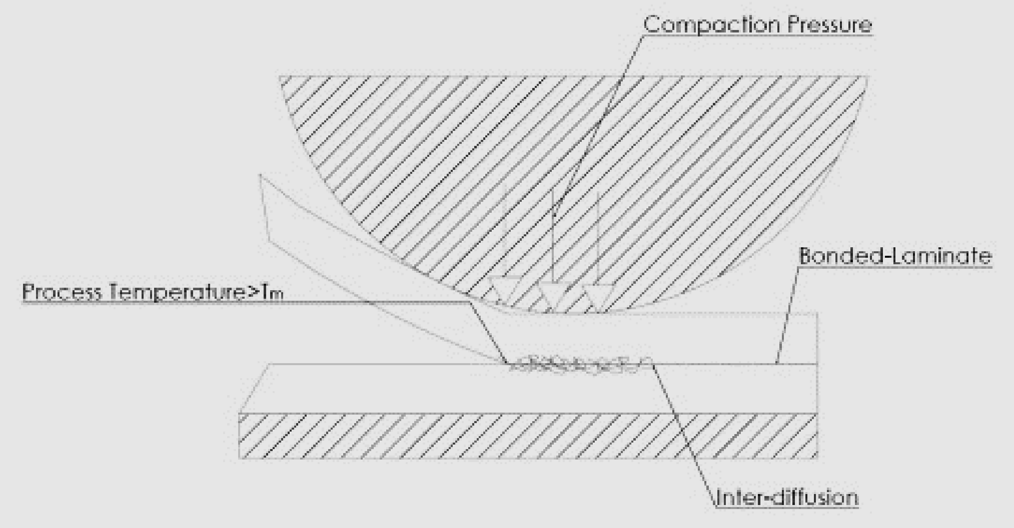


Parameters Affecting Process Outcome			
F	Compaction Force	Y	Beam profile
S	Compaction Area	I	Beam intensity
D_r	Roller Diameter	W	Beam size and shape
k_r	Roller Thermal Conductivity	β	Beam angle
T_r	Roller interface Temperature	Bi	Spot position bias
h	Heat Transfer Coefficient	α	Incoming tape angle
T_s	Substrate Temperature	τ	Tape Tension
T_M	Mandrel Temperature	X	Tape impregnation quality
k_M	Mandrel Thermal Conductivity	R	Tape Surface Roughness
D_M	Mandrel Curvature	t_{tape}	Tape thickness
N	Placement Rate		

Interlaminar bonding of thermoplastics layers an **important role** in tape placement processes!



i. intimate contact has to be achieved between the two layers and
ii. intermolecular diffusion, a process which is also known as healing, takes place between the surfaces in intimate contact



Laser-assisted tape placement process is characterized by the extremely short time available for bonding and consolidation

Test Specimen Fabrication

Laboratory at Institute for Advanced Composites and Robotics

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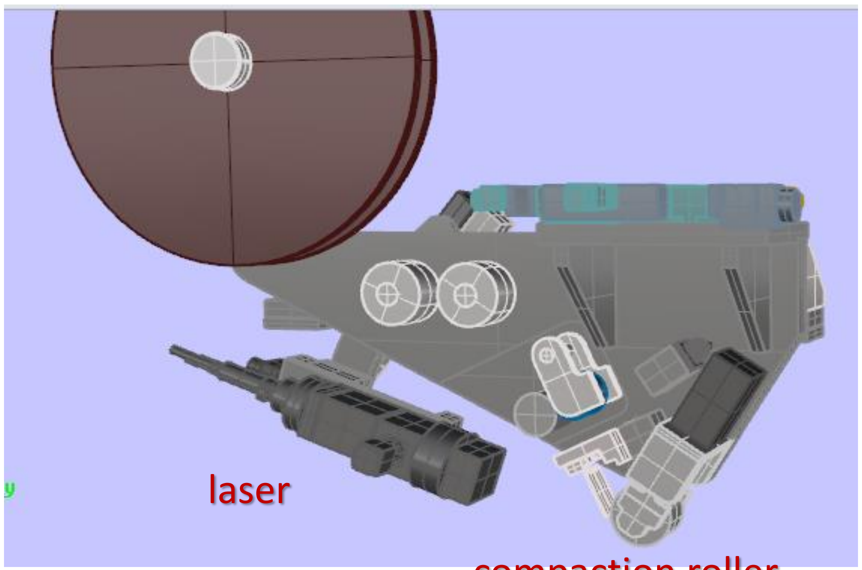

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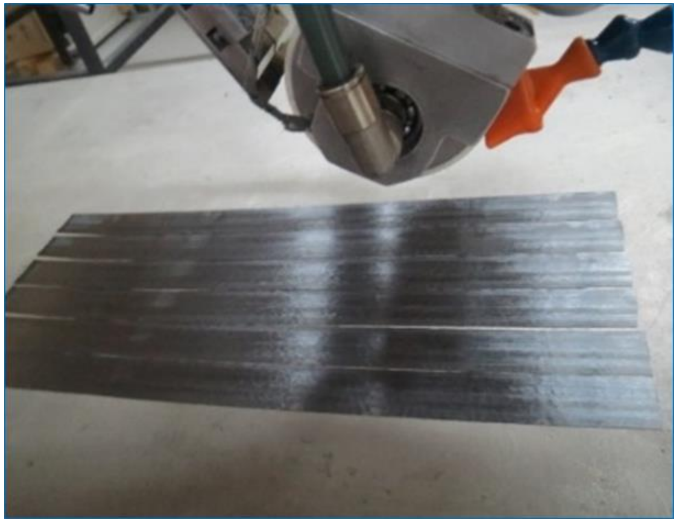
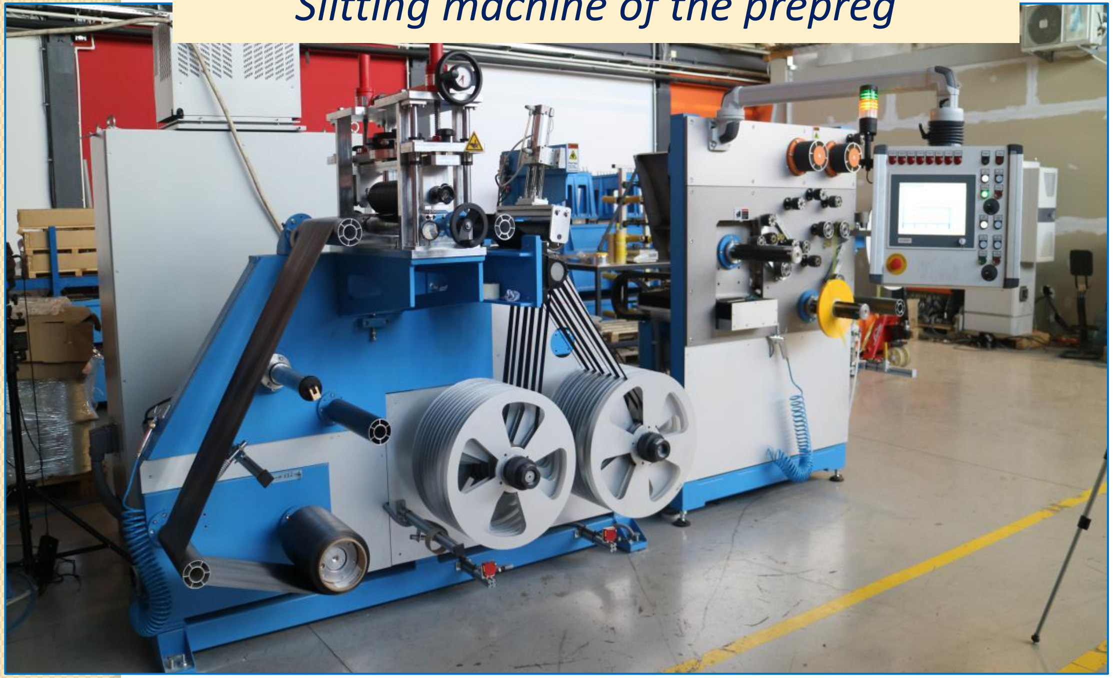


Slitting machine of the prepreg



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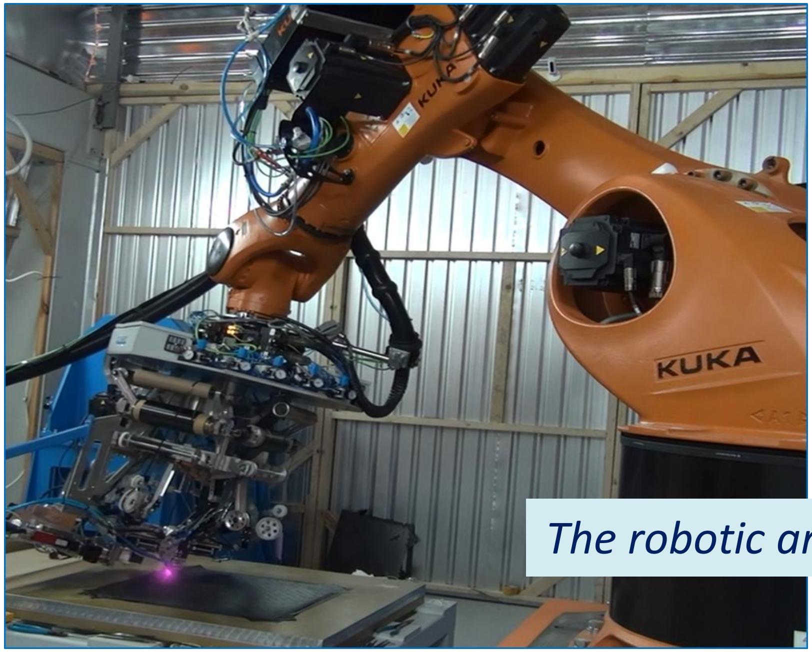
UD prepreg= 304,8 mm
slitting tape = 6,35 mm



The robotic arm with AFP head

$X_1X_2X_3$

Test Specimen Fabrication

Two types of thermoplastic unidirectional prepreg materials: UD1 and UD2.

UD1 prepreg: carbon fibres (AS4 carbon fibres) and thermoplastic matrices polyphenylene sulfide - PPS (Ticona 0214 PPS.)
UD2 prepreg: carbon fibres (AS4 carbon fibres) and thermoplastic matrices poly eter eter ketone PEEK (Vitrex 150 PEEK)

2^3 full factorial experimental design (FFED) by using of three parameters and two levels of variation.

1. The laser temperature – was taken to be the first factor,
2. Compact pressure of roller – second factor, and
3. Laser placement angle – the third factor.

Coding convention of variables for all samples

Sample designation **LATP-UD1**			
Code	**Laser temperature, °C**	**Laser angle, °**	**Compact pressure, N**
Zero level, $x_i = 0$	370	23,5	320
Interval of variation	10	1,5	50
High level, $x_i = +1$	380	25	370
Lower level, $x_i = -1$	360	22	270
Sample designation **LATP-UD2**			
Zero level, $x_i = 0$	450	23,5	457,5
Interval of variation	30	1,5	72,5
High level, $x_i = +1$	480	25	530
Lower level, $x_i = -1$	420	22	385

In order to include the whole study domain, we have chosen the central points of both ranges to be experimental points.

Factorial design 2^3

Experimental matrix								
Sample Designation		x_1	x_2	x_3	$x_1 x_2$	$x_1 x_3$	$x_2 x_3$	$x_1 x_2 x_3$
1	1-1 1-2	-1	-1	-1	+1	+1	+1	-1
2	2-1 2-2	+1	-1	-1	-1	-1	+1	+1
3	3-1 3-2	-1	+1	-1	-1	+1	-1	+1
4	4-1 4-2	+1	+1	-1	+1	-1	-1	-1
5	5-1 5-2	-1	-1	+1	+1	-1	-1	+1
6	6-1 6-2	+1	-1	+1	-1	+1	-1	-1
7	7-1 7-2	-1	+1	+1	-1	-1	+1	-1
8	8-1 8-2	+1	+1	+1	+1	+1	+1	+1

8 (2^3) trials

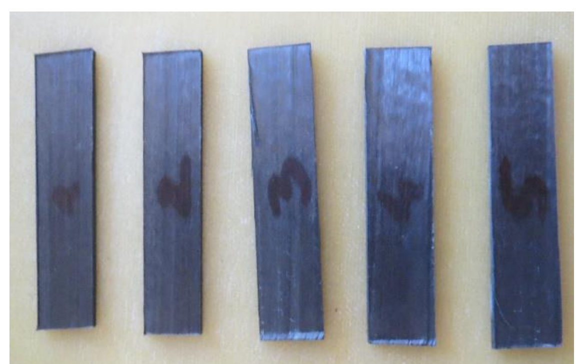
all possible combinations of the variables were tested

$X_1 X_2 X_3$

Conditions of the experiment

N	*Factors*				
	X_1 (°C)		X_2 (°)	X_3 (N)	
	LATP-UD1	**LATP-UD2**	**LATP-UD1 LATP-UD2**	**LATP-UD1**	**LATP-UD2**
1	380	480	25	380	530
2	360	420	25	380	530
3	380	480	22	380	530
4	360	420	22	380	530
5	380	480	25	270	385
6	360	420	25	270	385
7	380	480	22	270	385
8	360	420	22	270	385

Prepared samples



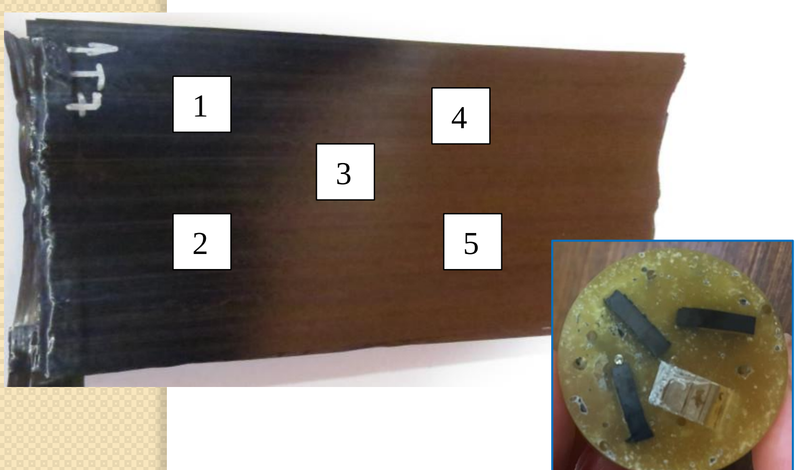
Mechanical characterization

$$\sigma_f = \frac{3F_{max}L}{2bd^2}$$

3pbt test

Microscopy analyses

Optical microscopy



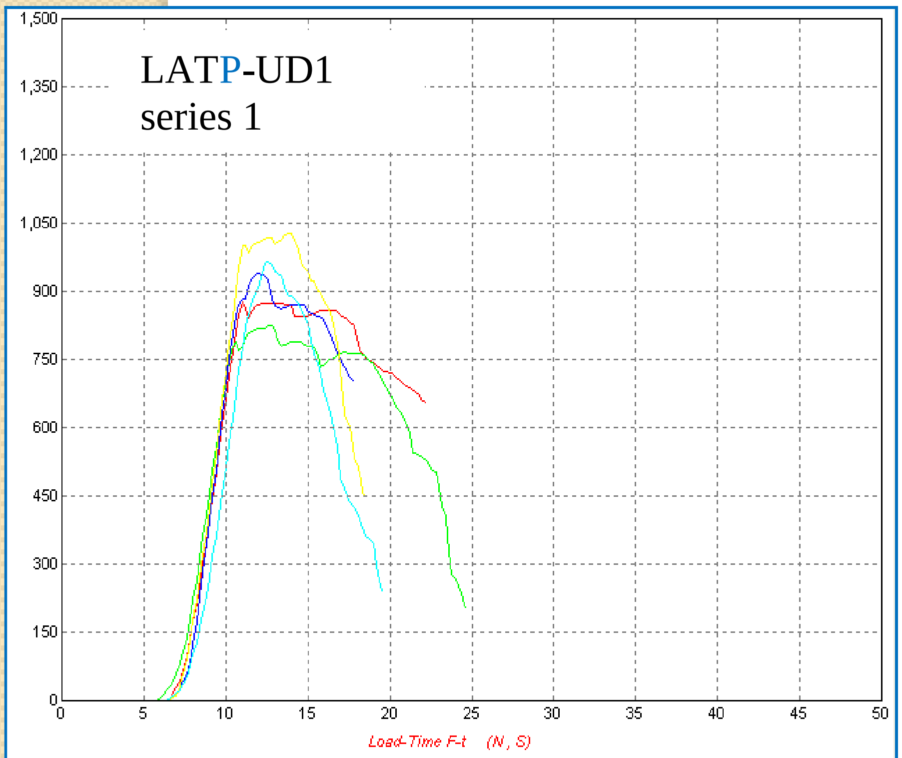
SEM microscopy

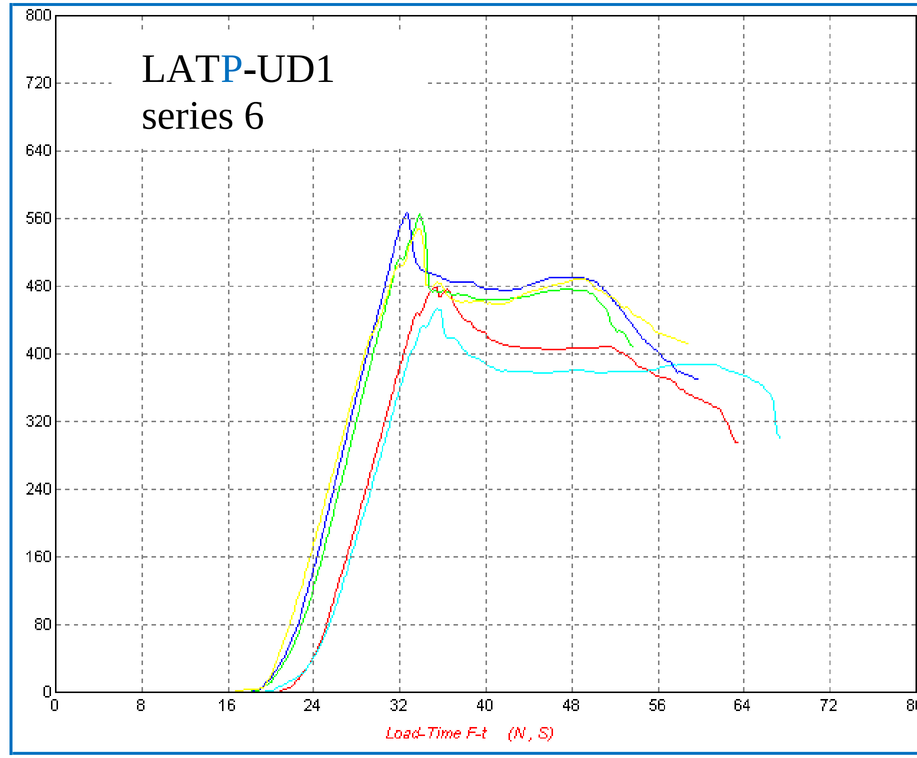
Results of the experiments: *Three-point bending tests of LATP – UD1*

N	y_{j1}	y_{j2}	y_{j3}	y_{j4}	y_{j5}	$\bar{y}$	S_j^2
1	975,77	980,43	1028,89	1120,00	1078,96	1036,81	3916,11
2	1026,43	955,57	932,83	862,76	931,07	941,73	13795,70
3	1010,29	1062,21	927,05	987,78	1070,17	1011,50	13709,17
4	837,18	963,41	1014,33	882,96	903,15	927,41	14355,64
5	869,12	815,17	931,19	977,36	926,56	903,88	3934,51
6	783,96	919,37	885,71	913,09	792,39	858,90	17352,05
7	847,68	858,76	919,25	991,11	992,34	921,83	19254,82
8	922,32	901,20	840,96	943,84	853,55	892,37	7773,27
$\sum_{N=1}^{8} S_j^2$							78390,14
$\frac{\sum_{N=1}^{8} S_j^2}{8}$							9798,768121
S_{bi}^2							244,9692
Δbi							30,67

$$y = 936{,}80 + 31{,}7X_1 - 1{,}47X_2 + 42{,}56X_3 + 3{,}31X_{12} + 13{,}09X_{13} + 11{,}38X_{23} - 0{,}57X_{123}$$

Load -time diagrams for LATP-UD1: series 1 and series 6





The test results indicated an effect of compact pressure of roller and laser temperature on mechanical properties of composite specimens. Namely, the bigger compact pressure of roller and higher laser temperature led to a higher flexural properties of laminate panels.

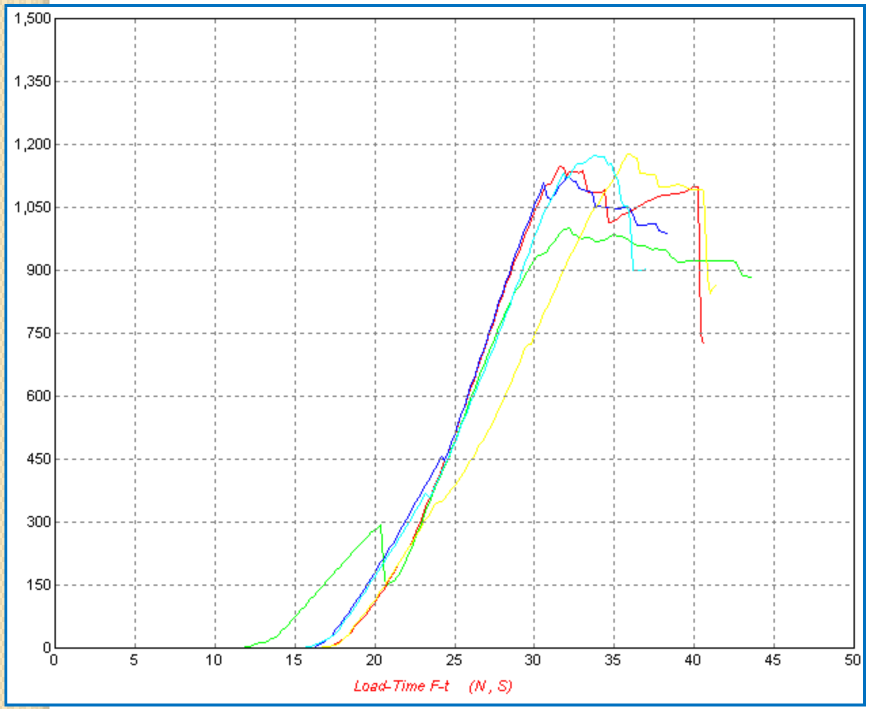
Results of the experiments: *Three-point bending tests of LATP – UD2*

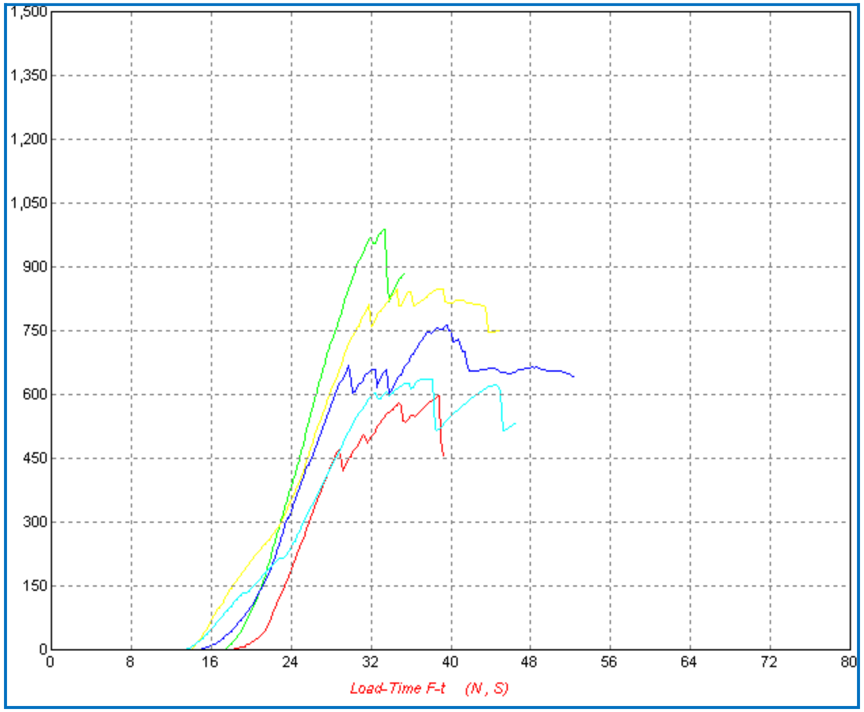
N	y_{j1}	y_{j2}	y_{j3}	y_{j4}	y_{j5}	$\bar{y}$	S_j^2
1	1118,66	976,34	1129,85	1184,31	1284,20	1138,67	12522,40
2	990,66	914,16	822,52	1087,40	1061,23	975,20	47264, 00
3	954,72	1019,28	1024,54	872,62	1082,32	990,69	25593,43
4	821,73	1087,31	945,38	942,10	1002,39	959,78	37658,48
5	1033,95	954,48	915,45	896,35	1066,89	973,42	5514,90
6	684,00	885,37	708,09	755,40	787,26	764,03	24870,07
7	1159,59	857,46	1034,88	1025,20	1071,14	1029,65	48302,27
8	842,06	1031,63	795,32	837,97	940,19	889,44	36549,96
						$\sum_{N=1}^{8} S_j^2$	202197,91
						$\frac{\sum_{N=1}^{8} S_j^2}{8}$	25274,7383
						S_{bi}^2	631,8685
						Δbi	49,20

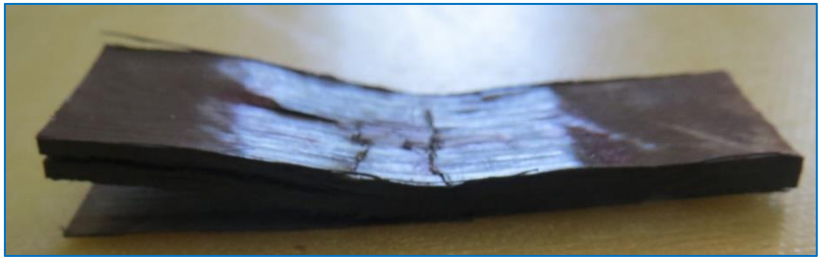
$$y = 965{,}11 + 68{,}00X_1 - 2{,}28X_2 + 50{,}98X_3 + 25{,}22X_{12} - 19{,}40X_{13} + 43{,}13X_{23} + 7{,}92X_{123}$$

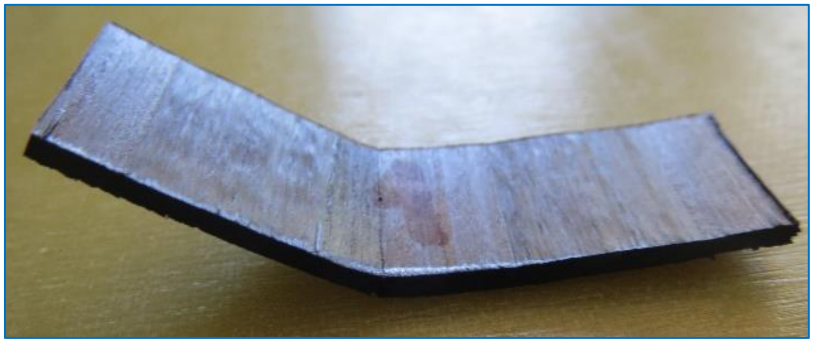
the main positive contribution to the y is given by the laser temperature and the compact pressure of roller

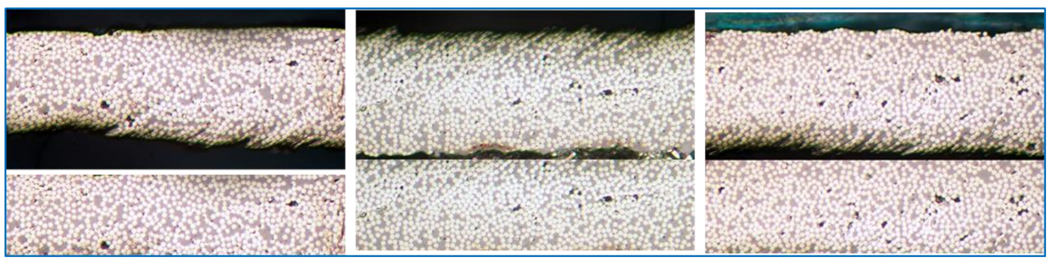
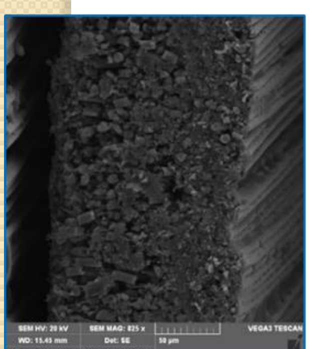
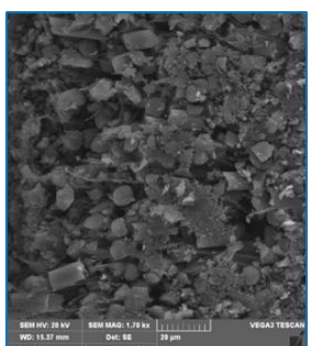
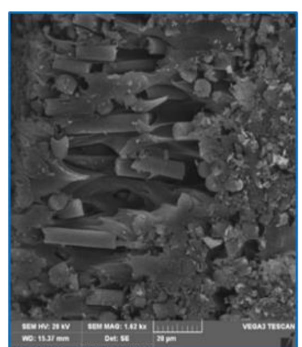
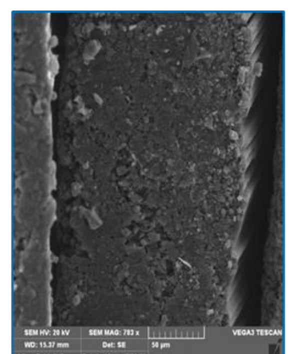
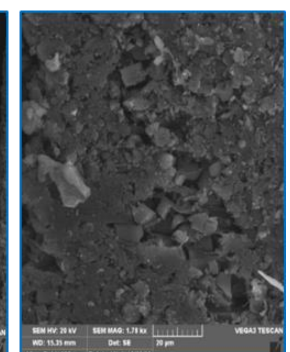
Load -time diagrams for LATP-UD2: series 1 and series 6









CONCLUSION

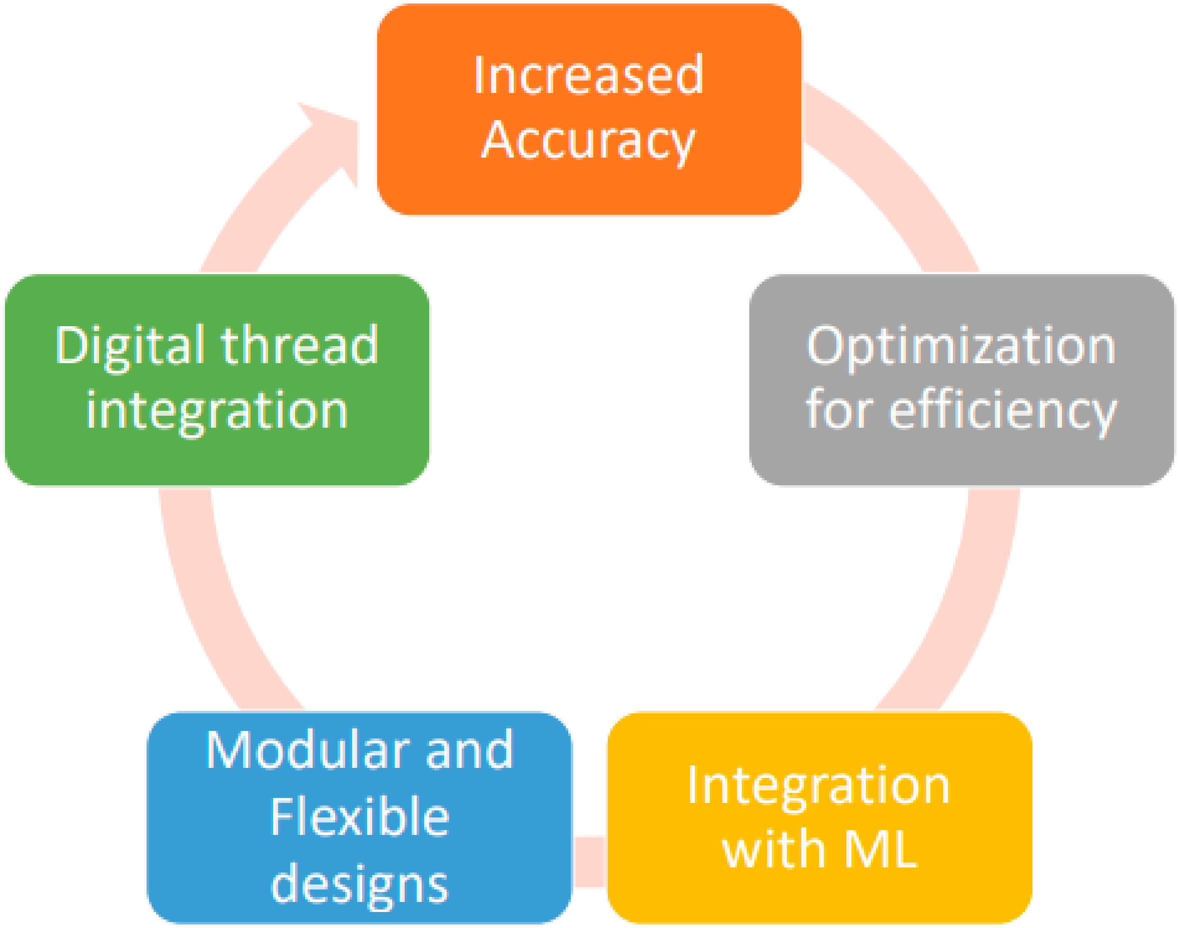
It can conclude that high quality of laminates made by LATP process depends on the processing parameters fed to the LATP system. The compaction force applied during the lay-up process and the laser temperature play a crucial role in achieving of obtaining of defect-free laminates using the thermoplastic (UD1 and UD2) prepreg materials.

Experimental measurements of the flexural strengths of composite pipes for determined ranges of parameters have been carried out implementing full factorial experimental design.

Regression equations were established for flexural strengths as a function of the compact pressure of roller, laser temperature and angle of laser. The experimental procedure described in the present work is sufficient to show the influence of the parameters on the flexural properties of thermoplastic composites (LATP-UD1 and LATP-UD2) produced by laser-assisted automated tape laying process.

The test results indicated that the change of the compact pressure of roller and laser temperature cause a variation in the final mechanical results, whereas the influence of the other parameter: angle of laser is much lower, and the interaction of the factors has a negligible effect on the response. Very good agreement has been found between experimental and calculated values. It was observed that if the study domain is precisely established (narrow enough), the full factorial experimental design can be employed to give good approximation of the response, i.e. stress of peak values.

FUTURE FOR COMPOSITE MANUFACTURING



Thank you