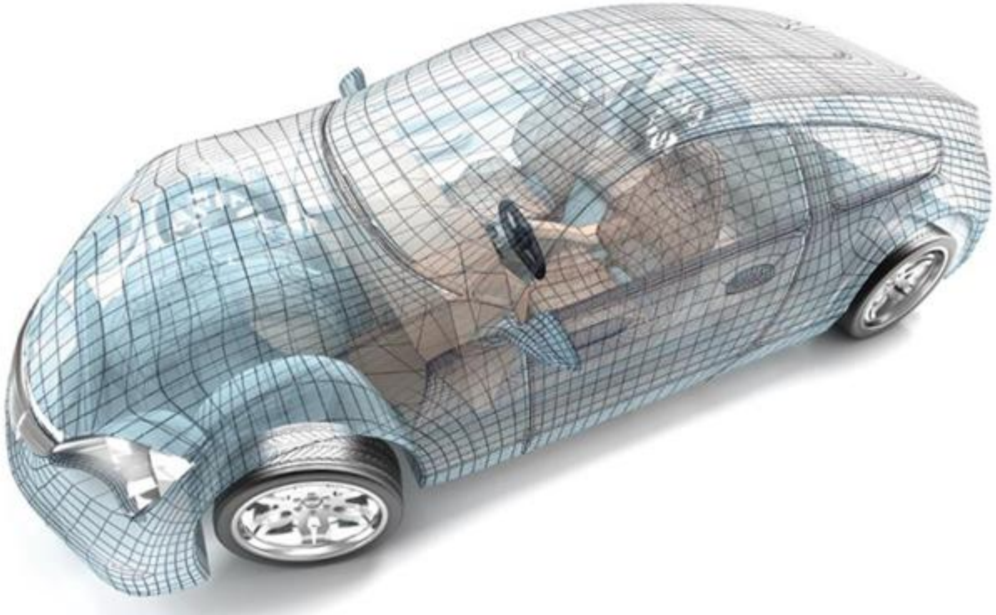
TCC 2020

THERMOPLASTIC COMPOSITES CONFERENCE

A VIRTUAL EVENT

APRIL 29 – MAY 1, 2020



Advances in Automated and Tool-less Layup of High-Temperature Thermoplastic Parts

Presented By: Vele Samak
Vice President
Mikrosam

AGENDA

- MIKROSAM Introduction
- Raw material quality Issues
- Testing optimal ILSS parameters for AFP of thermoplastics parts
- Comprehensive test results and challenges for large airplane part
- Transitioning to Dual Robot
- Experiences, challenges and results of Dual Robot
- Next steps in this direction
- Video show
- Q&A

MIKROSAM COMPANY HIGHLIGHTS

Company established	1990 – 40+ years composites know-how from civilian and military applications
Strategic focus	Engineered-to-order machines in all advanced areas of making composite parts
Technical areas	Composites production expertise Motion control and process automation Specialized software development Joint R&D in new composite manufacturing
Workforce	Engineers: 60% Production personnel: 31%
General Activities	Manufacturing, R&D, Education

> 260
machines & production lines delivered

> 40
countries

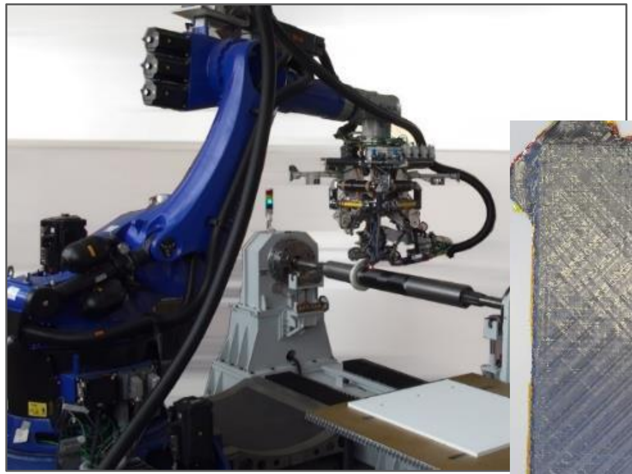
AFP/ATL, CNG/H2, FW
fastest growing segments

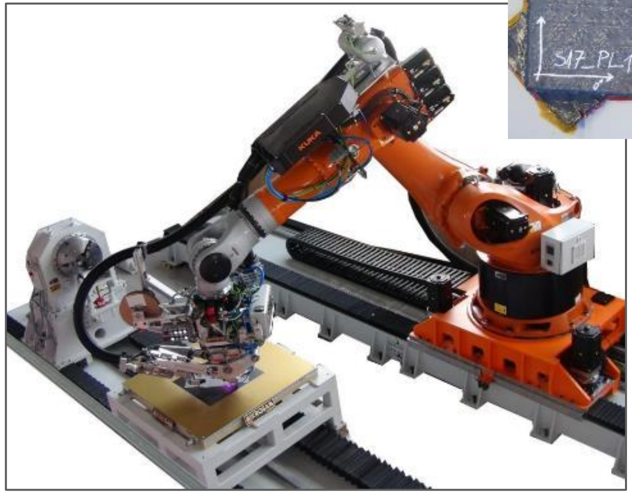
#1 Europe, #2 Asia, #3 USA, #4 Russia
>90% of global sales and priority markets

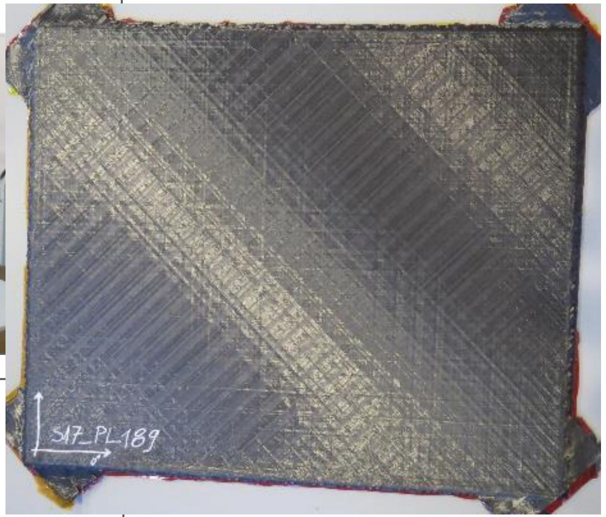
USA, Europe & China fastest growing markets

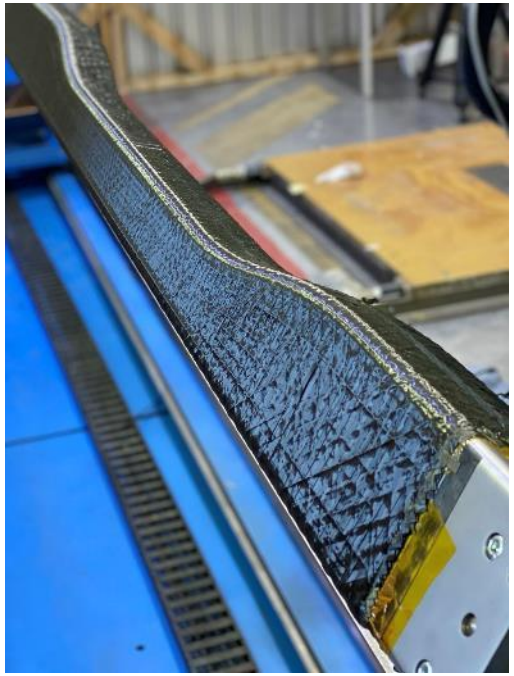
30th anniversary
MIKROSAM®
CONTROL • AUTOMATION • ROBOTICS

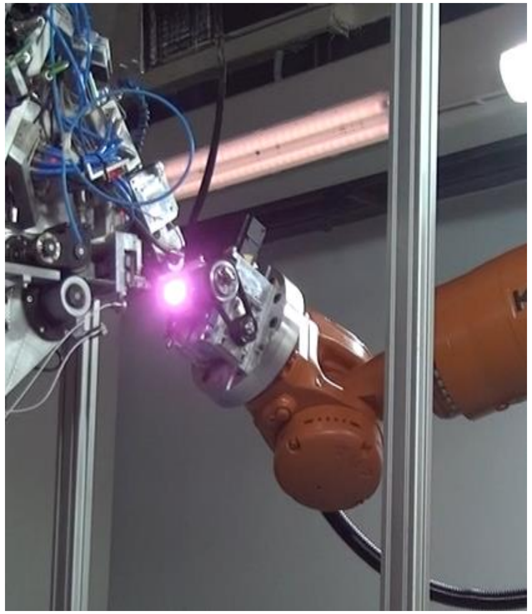
KEY TAKEAWAYS: FROM AFP OF FLAT PANELS, TO COMPLEX PARTS AND TOOL-LESS LAYUP

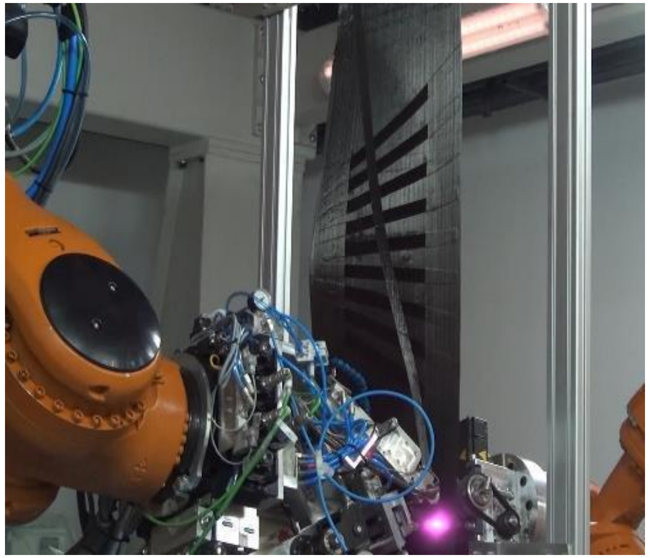










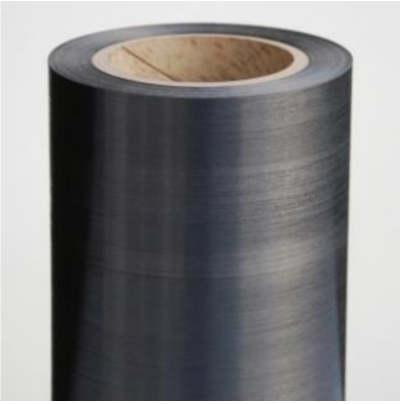


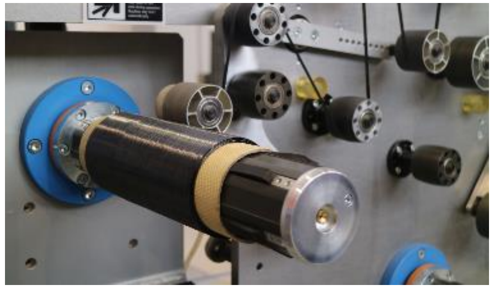
STEP 1: SLITTING OF THERMOPLASTIC UD TAPE AND RAW MATERIAL QUALITY

Materials for Experiment

Complete line with all equipment units and software solutions

Thermoplastic Unidirectional Prepreg (UD)

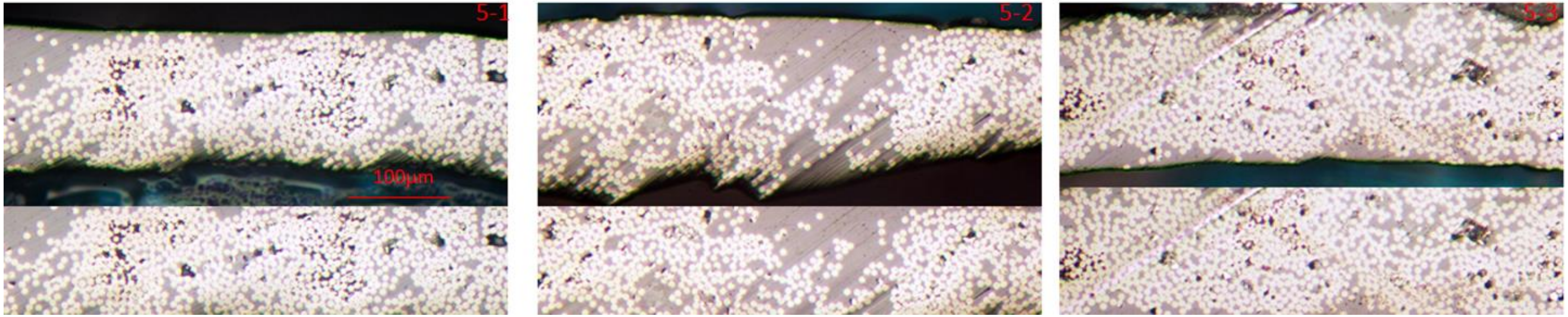




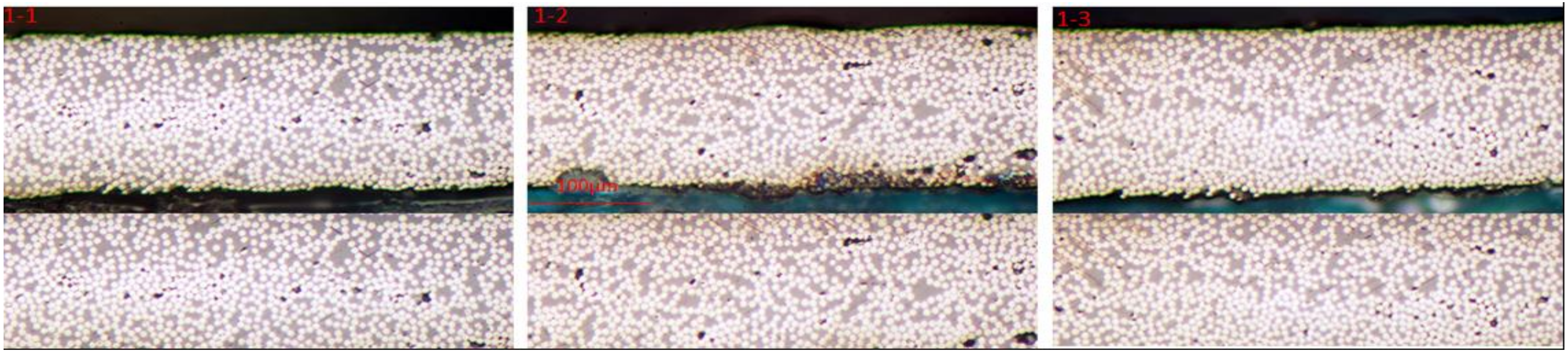
300 mm to 6.35 mm (including rewinder)

Analysis of lamina - Calculating of voids

Voids with optical microscope - 6 samples x 3 repetitions, 18 images total

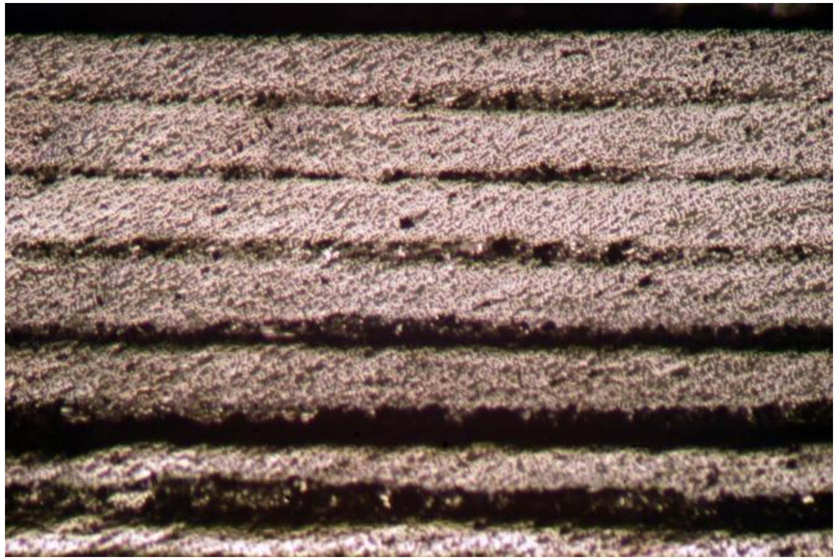


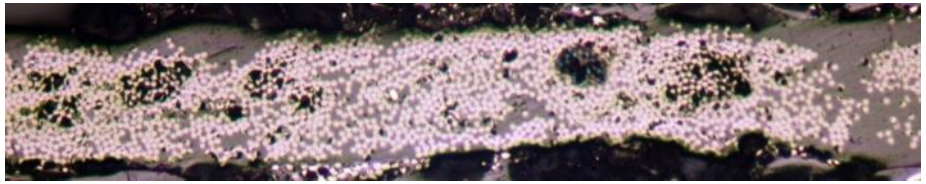
Sample 3 UD 145 gsm Material A)



Sample 1 UD 145 gsm Material B)

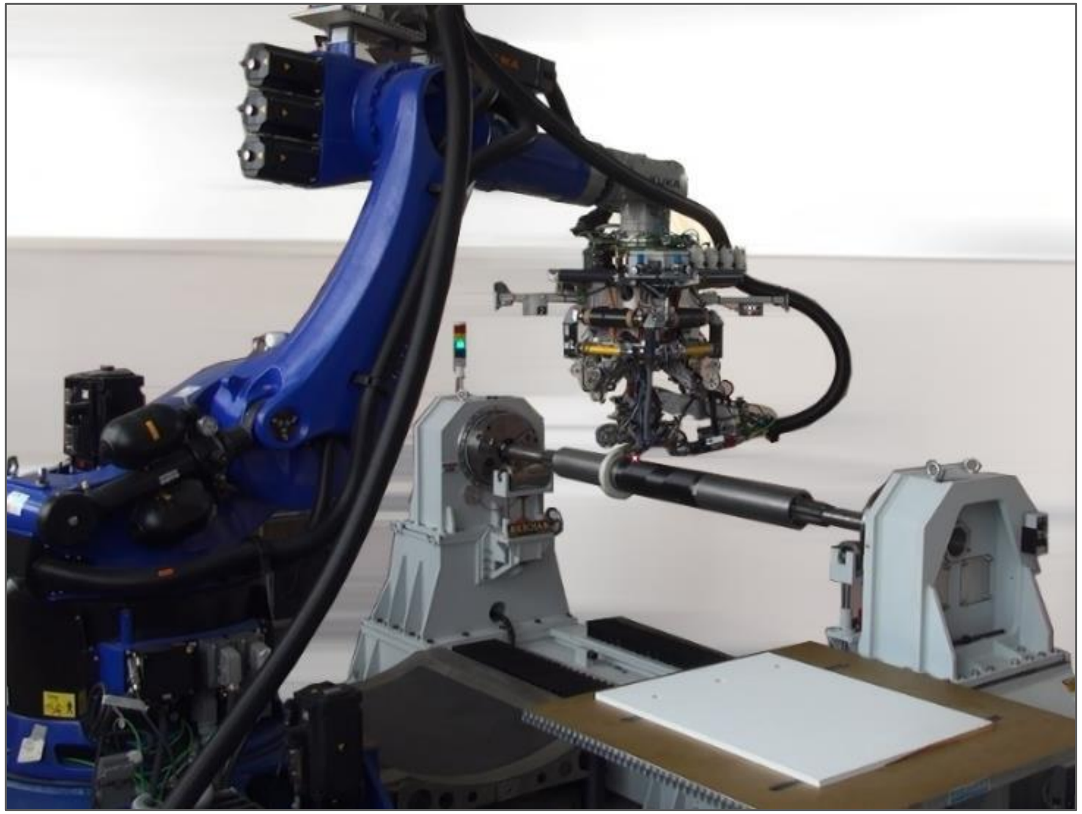
SUPPLIER VARIATIONS ARE STILL AN ISSUE FOR QUALITY AFP EXAMPLES: PPS PREPREG (LEFT), PEKK PREPREG (RIGHT)





- The influence of 3 parameters on ILSS of thermoplastic samples:
  - temperature of laser
  - temperature of tool
  - laser angle
- ILSS tested on universal testing machine
- UD thermoplastic prepreg PEEK 12K 145/34 – (6.35mm wide and a thickness of 0.14 mm)
- Laminates comprises 16 plies with thickness ~ 2,2 mm
- Steps in ILSS Testing:
  - Sample preparation according to EN ISO 14 130 standard (ASTM D2344)
  - Calculation of ILSS and voids of samples
  - Determination of parameters affecting the shear strength

MIKROSAM'S STATE-OF-THE-ART AFP AND ATP: MODULAR, UPGRADEABLE AND RECONFIGURABLE WORK CELLS



AFP with ¼” or ½” tows (4, 8 or 16) or **Single-tape** up to 2” wide

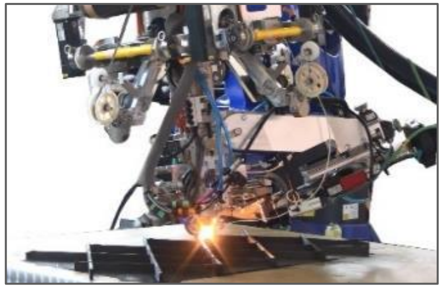
Multi-material Heads: Thermoset, Thermoplastic, and Dry-fiber

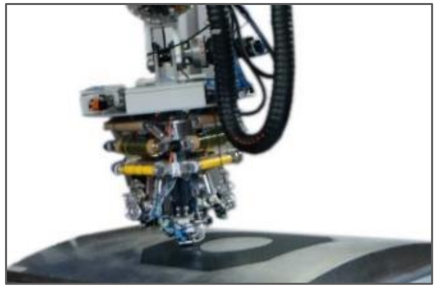
Standard Kuka robot

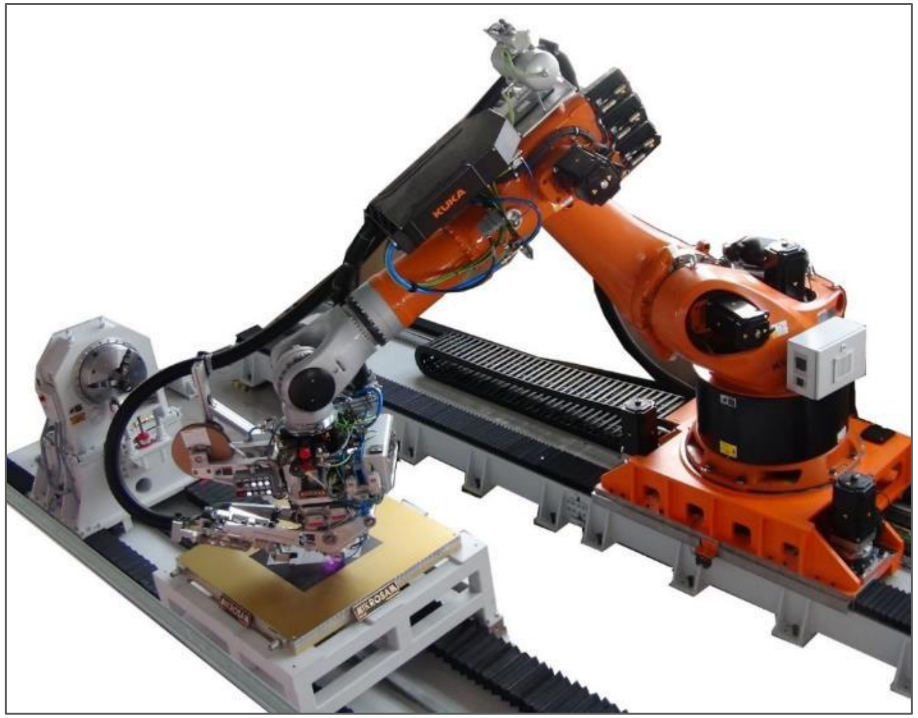
Exchangeable Heads for rapid testing and high reliability

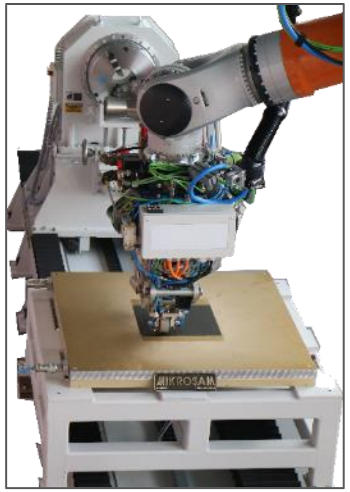
Temperature control table

Head design for reliable use, easy service, and quick maintenance









CONSTANTS AND VARIABLES FOR LAFP PROCESS

- Roller temperature = 20ºC
- Fiber = Carbon HTS45 12K
- Resin = PEEK
- Heat source = Laser
- Lay-up speed = 167mm/s
- Contact roller pressure – compaction force ~400N
- Type laser LDM 3000 100
- Optic - LL1.7/LL1.5 33x43mm

Constants in process

- Temperature of process
- Tool temperature
- Laser angle

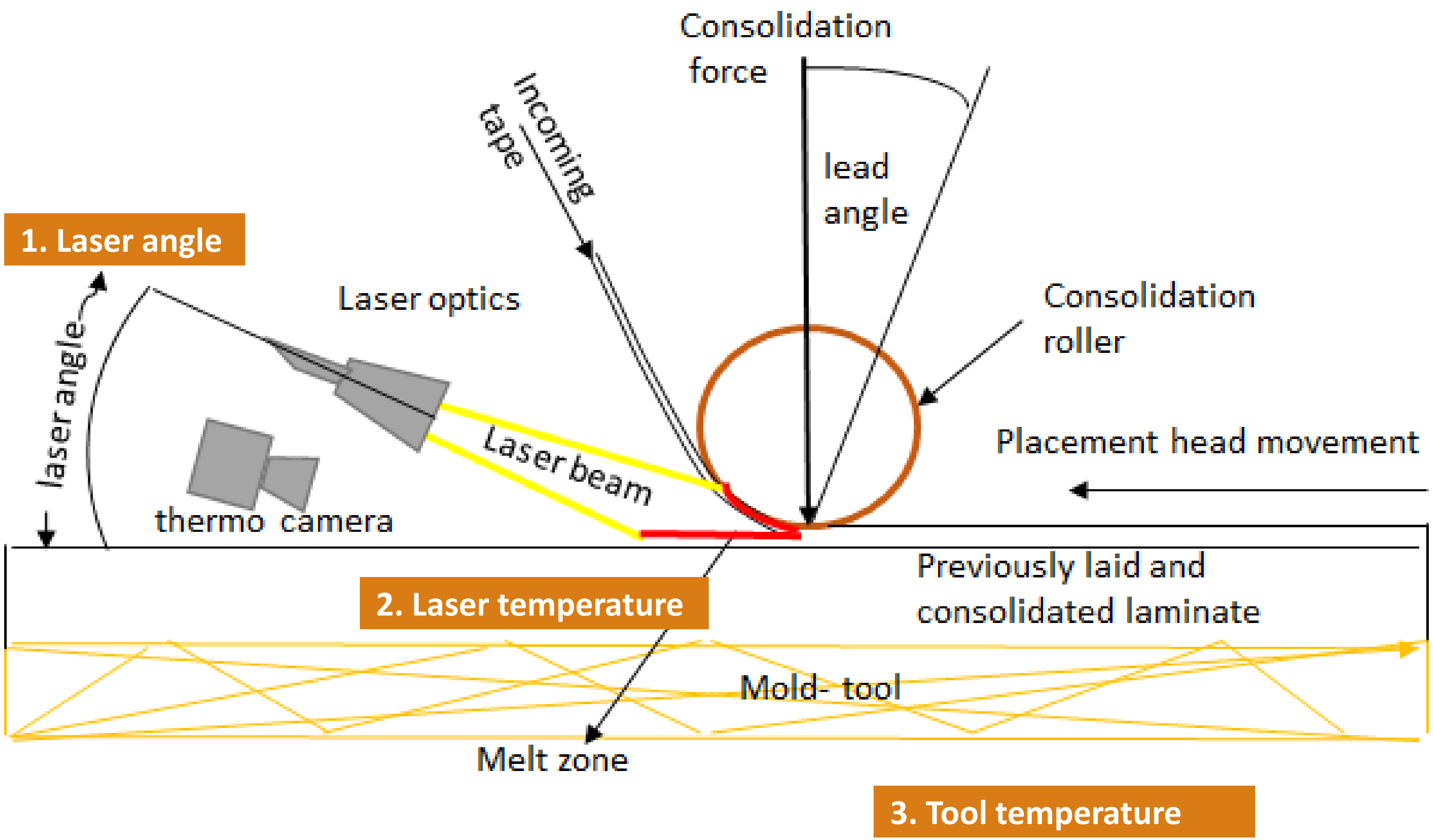
Variables in process

Manufacturing parts Laser AFP process

Results

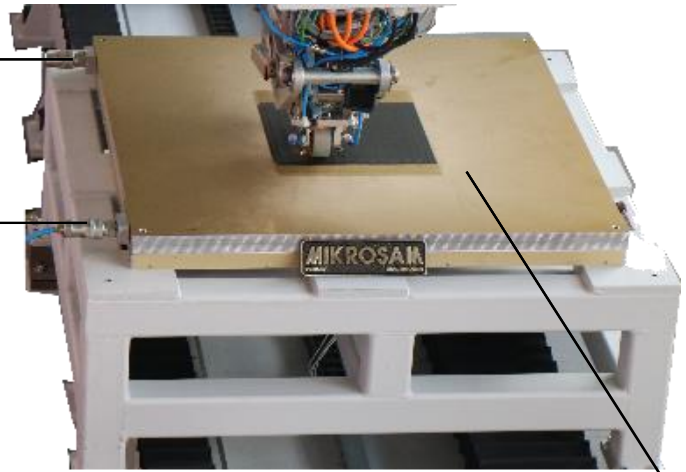
Calculate ILSS + voids

LAFP – LASER-HEATED AUTOMATED FIBER PLACEMENT PROCESS: THREE VARIABLES IN EXPERIMENT

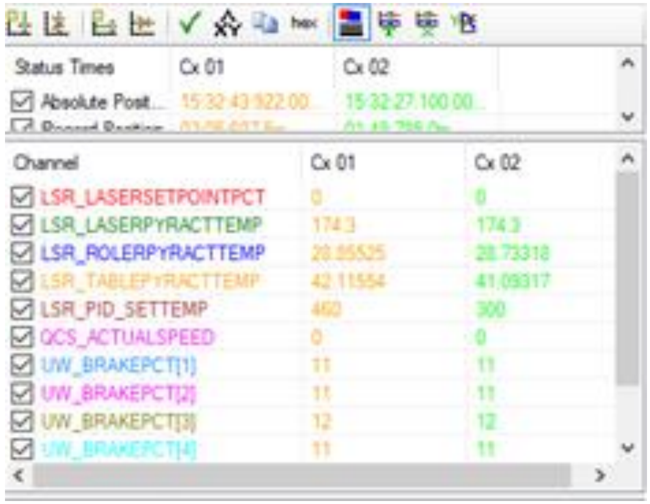


VARIABLE 3: TABLE TEMPERATURE

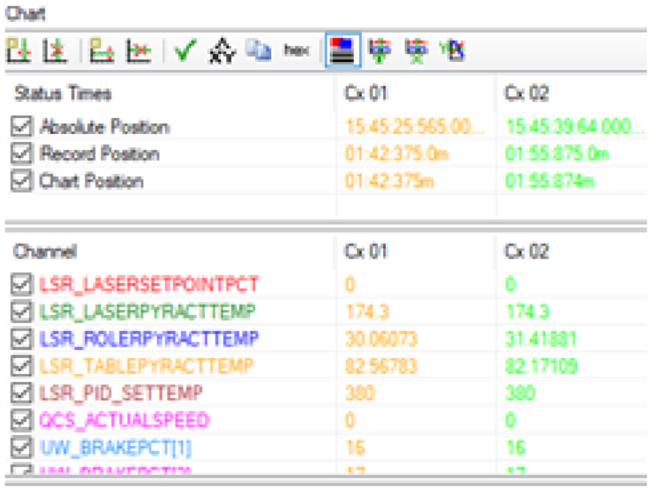
Thermoregulation:
Water +40C up to +140C
Diather oil +40C up to +200C



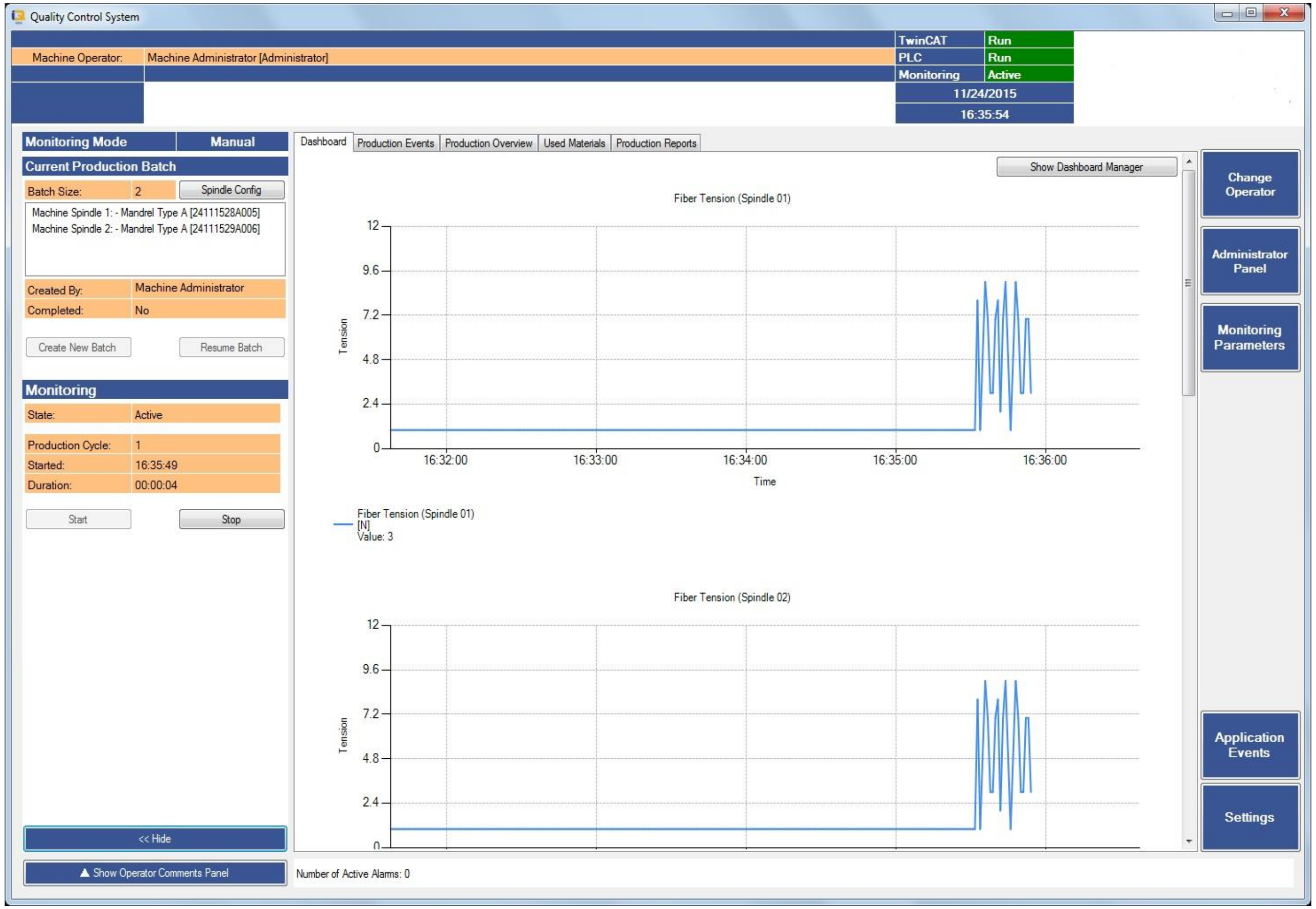
T =40°C

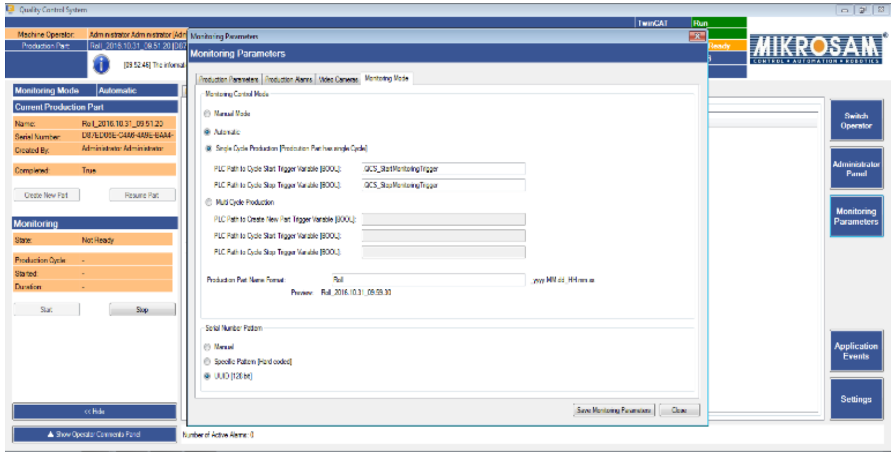


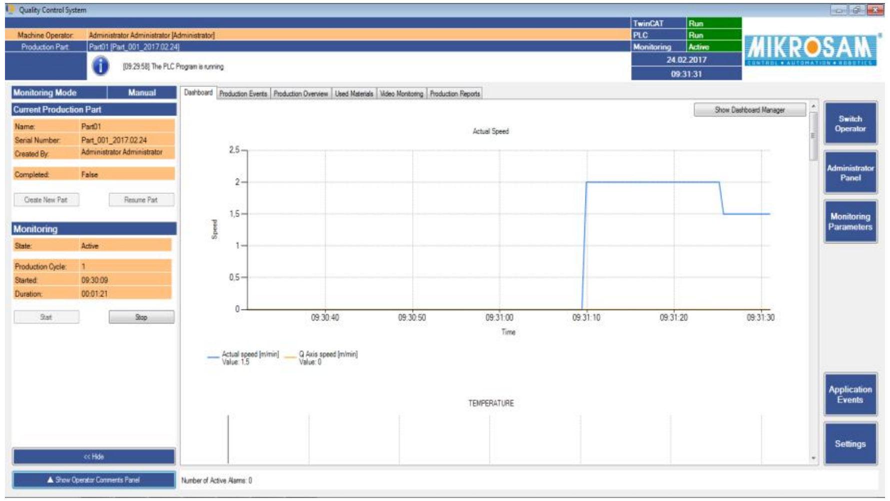
T =80°C



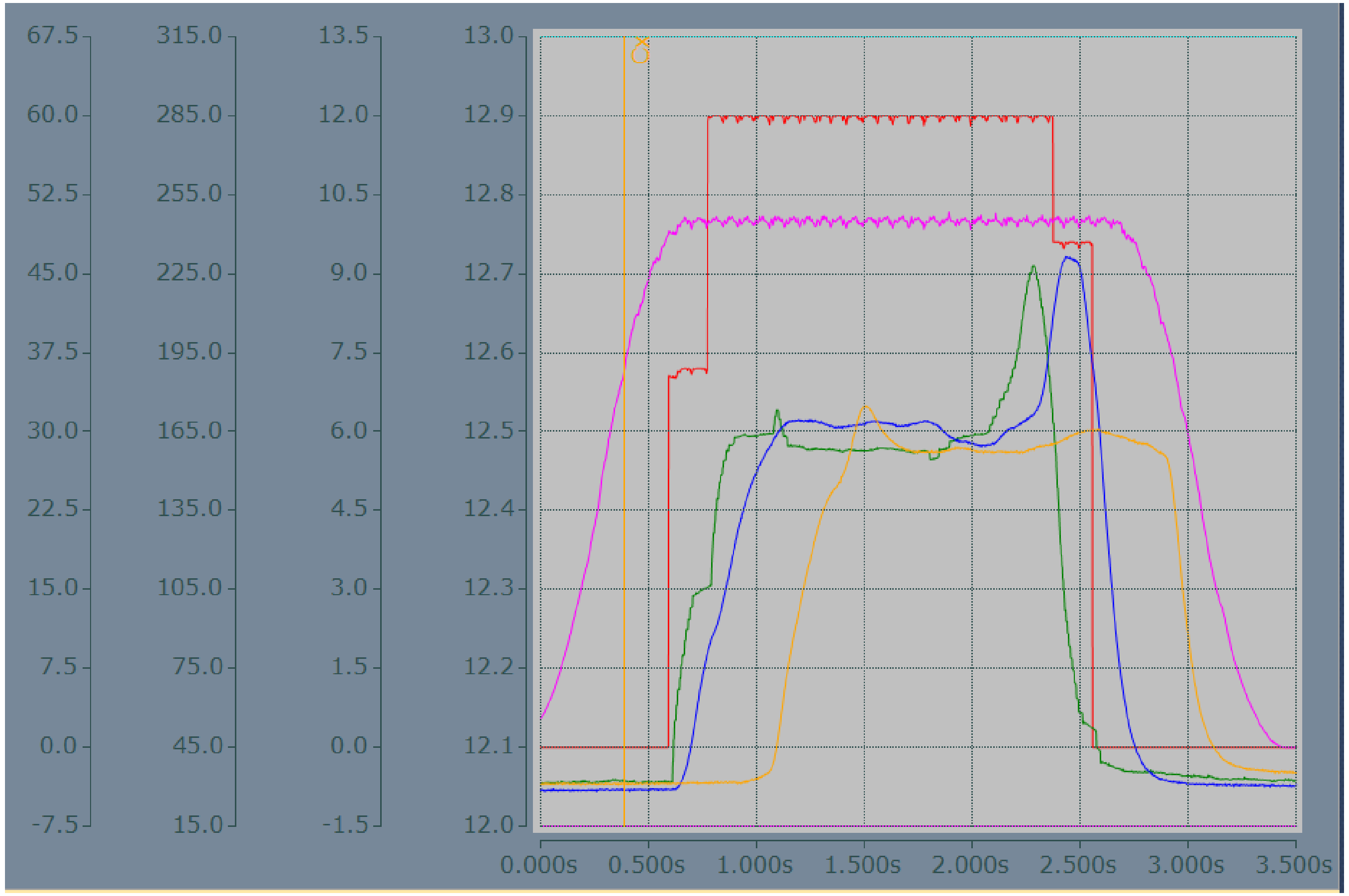
Quality Control System (QCS)

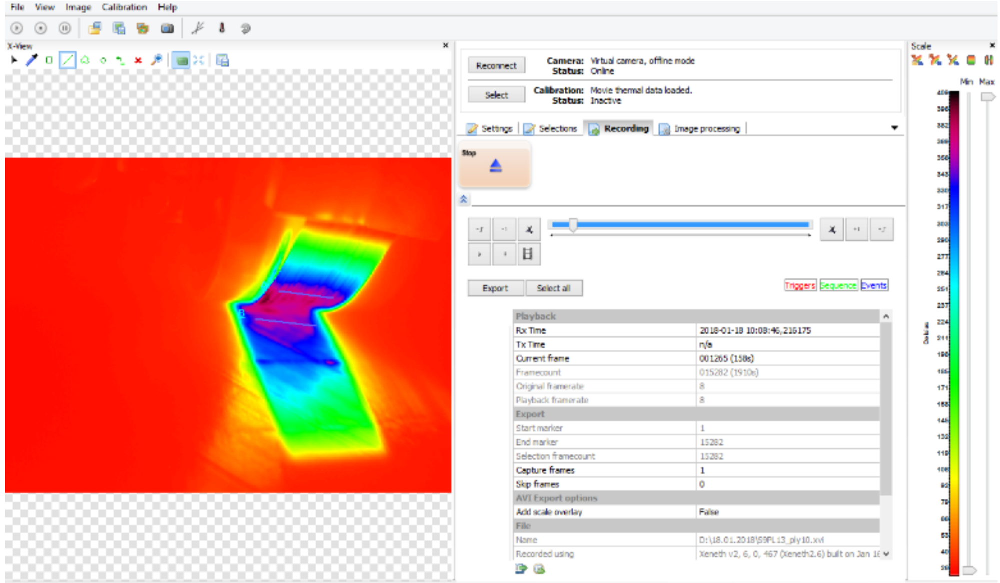


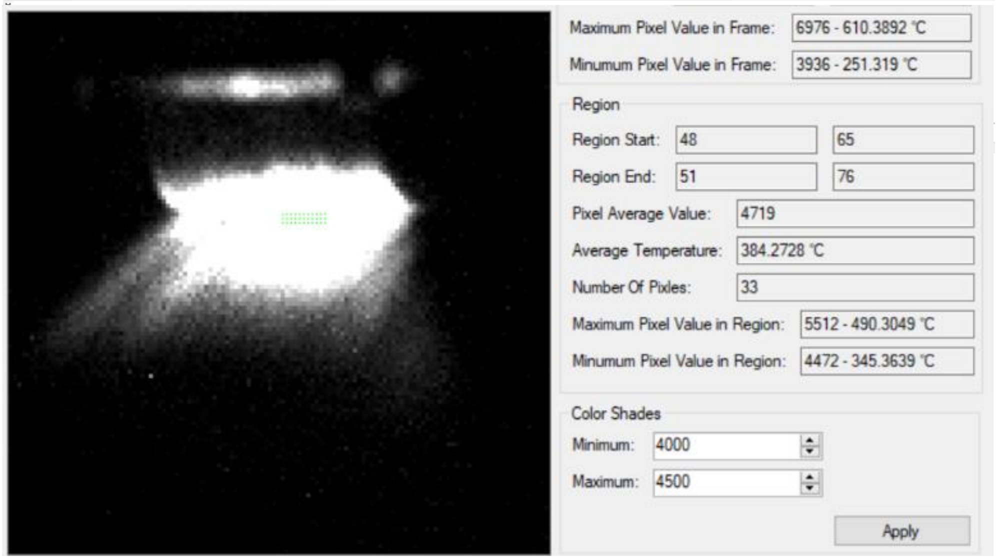




THERMAL MODEL

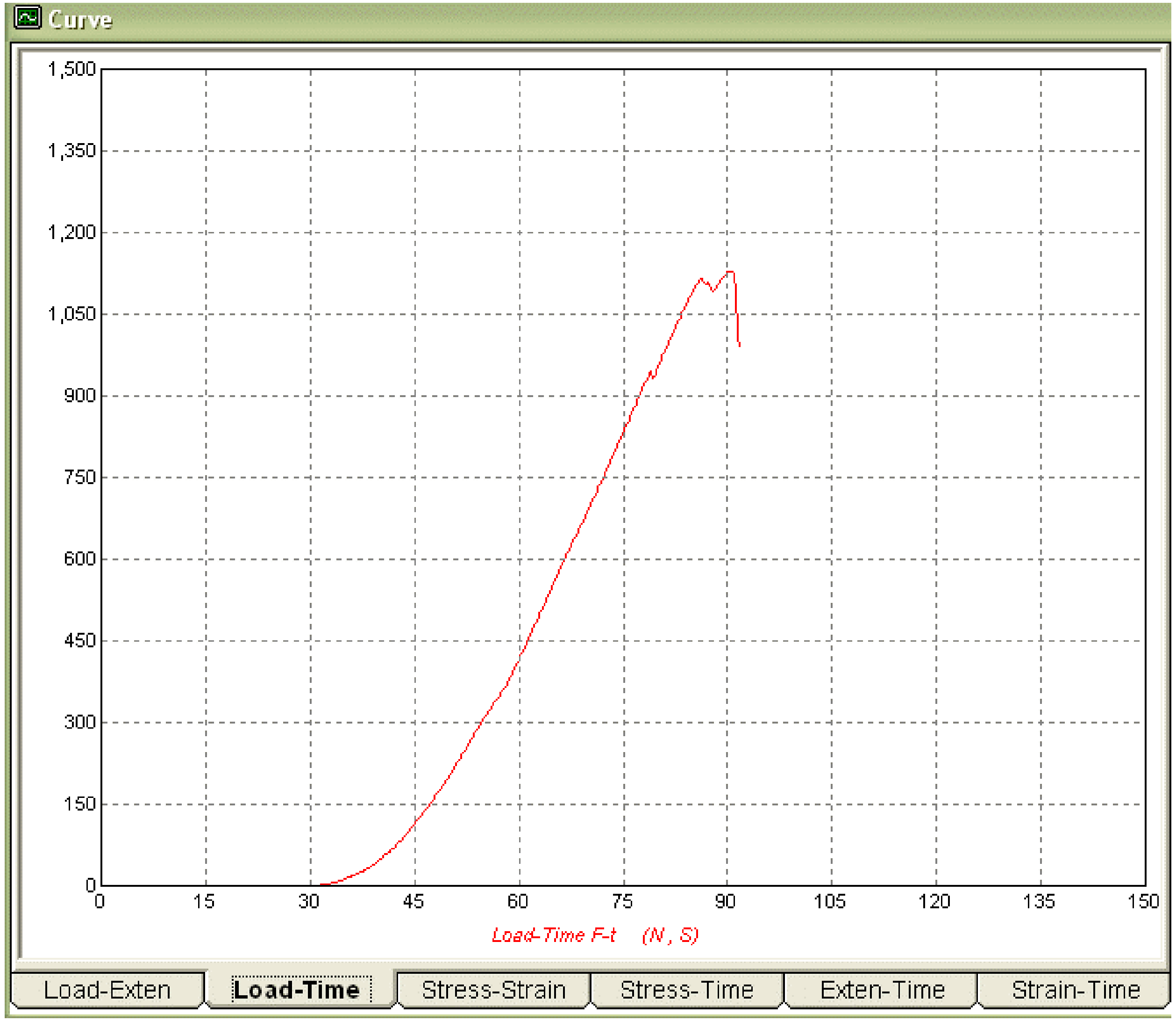






SAMPLES TESTING

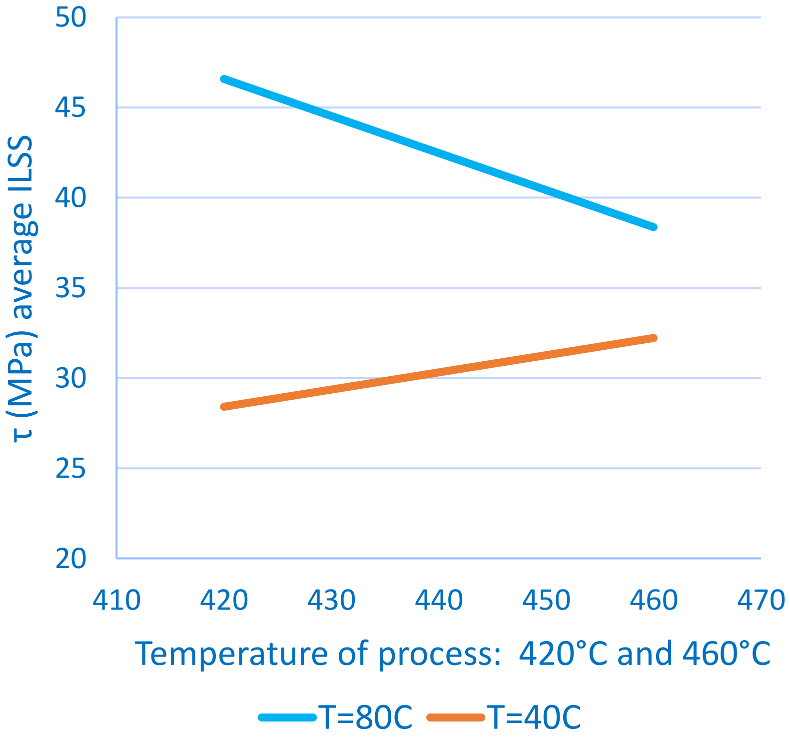
Universal Testing machine



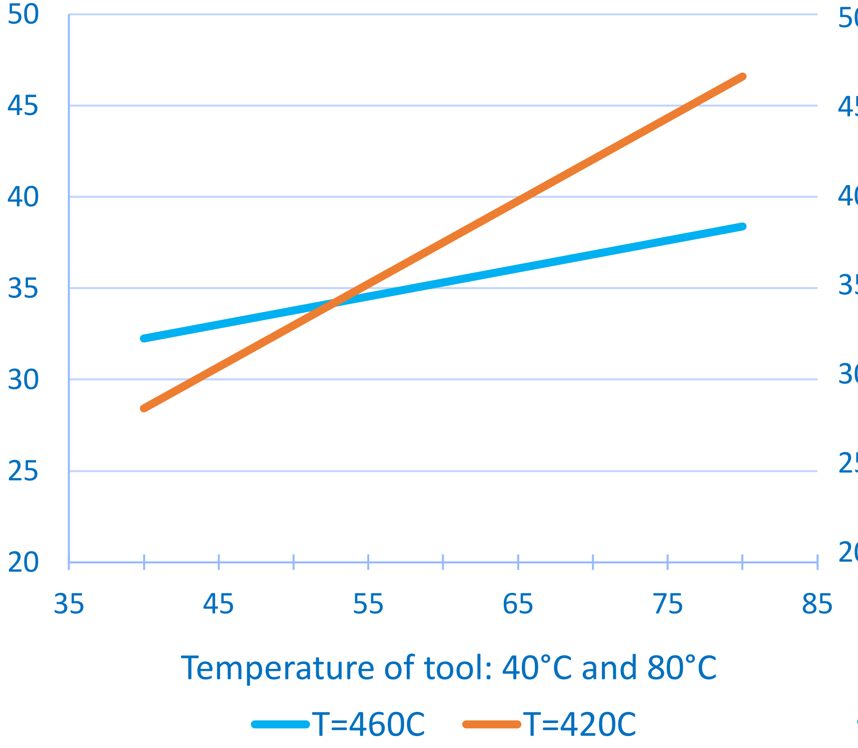
Force-time diagram of No.6-3 sample for LAFP

TESTING THERMOPLASTIC SAMPLES FOR ILSS: REDUCING LASER TEMP, HEATING TABLE, FOCUS LASER ON SURFACE IMPROVES ILSS

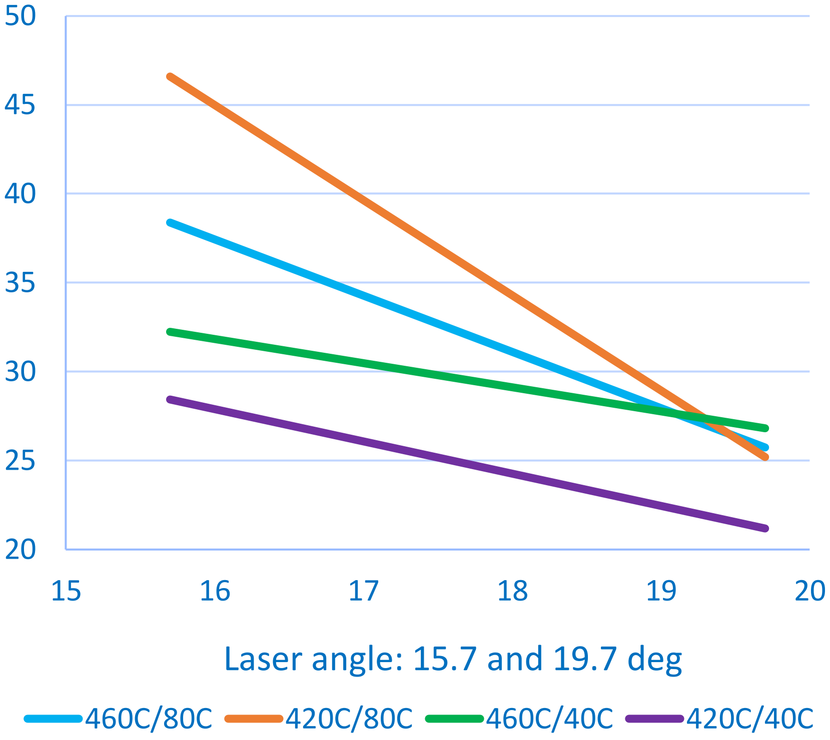
ILSS vs temperature of laser X1



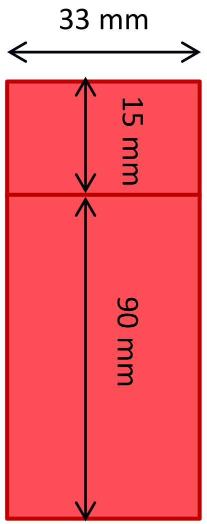
ILSS vs temperature of table X2

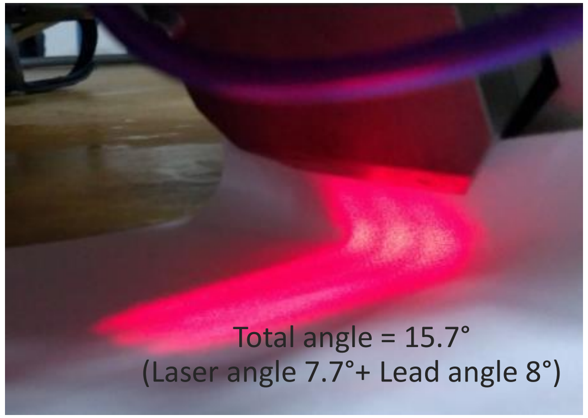


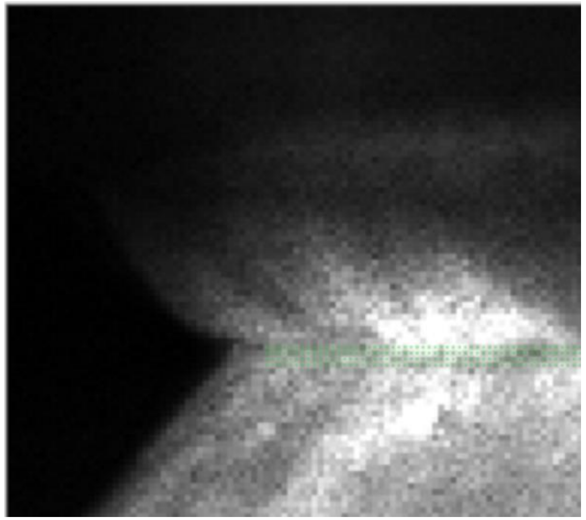
ILSS vs laser angle X3

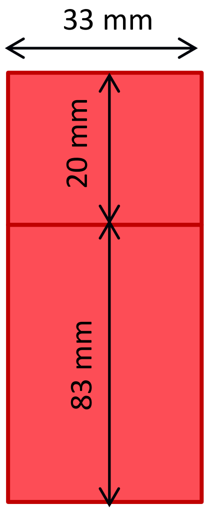


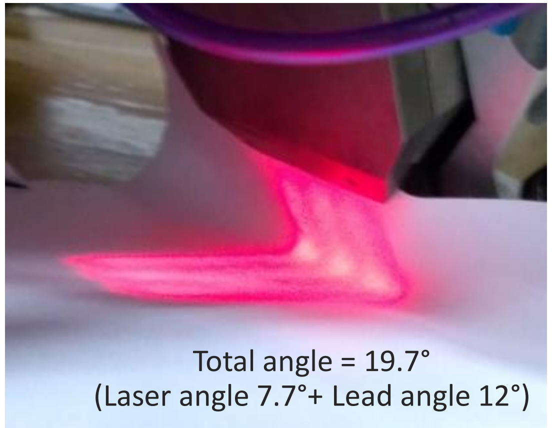
LASER ANGLES IN ATP/AFP: ANGLE CAN DEFINE PURPOSE OF ATP OR AFP

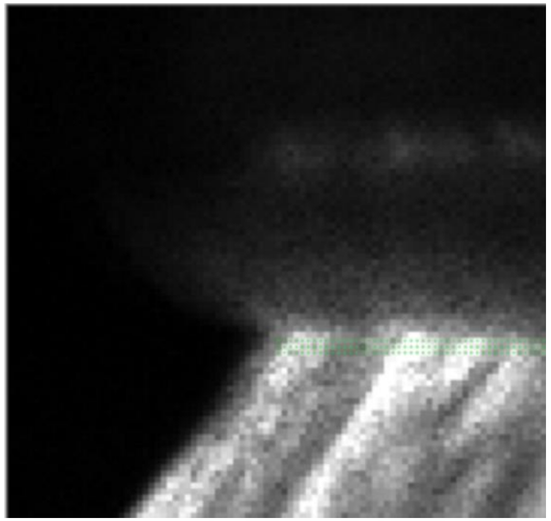












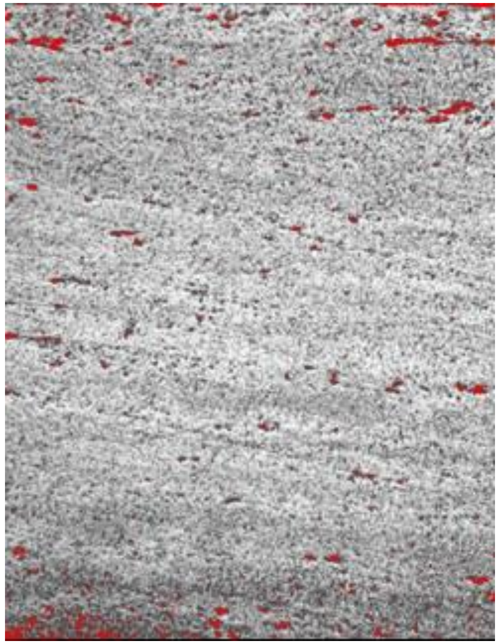
Determining the heat distribution between the roller and the laminate on the thermal camera software Best heat distributions between roller and laminate is obtained for angles combination from measurement 2:

Laser angle = 7.7°, Lead angle = 8°, Total angle = 15.7°

LOW POROSITY LAMINATES MANUFACTURED WITH LAFP: UD (left), QI (right)

Voids percentage: **1.65 %**

x50



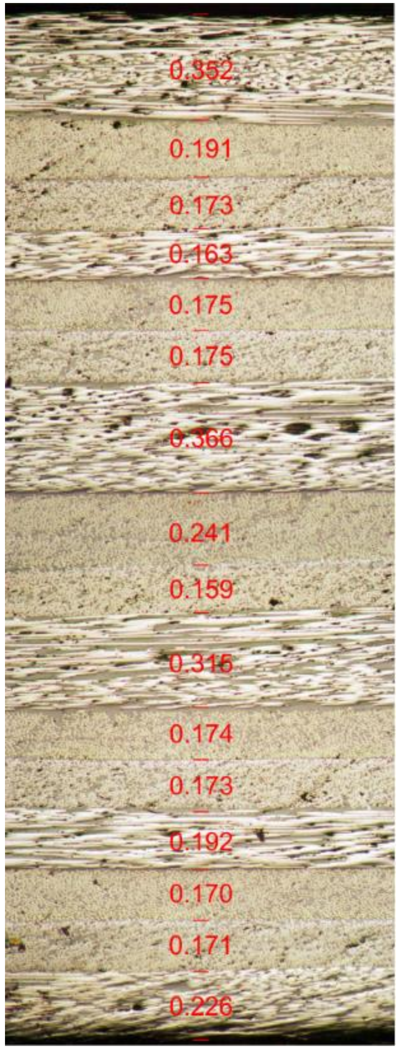
x100

Design: 90°/45°/-45°/90°/45°/-45°/90°/90°/45°/-45°/90°/90°/45°/-45°/90°/45°/-45°/90°/90°
Pressure: 3.8 bar
Temperature of laser: 320°C
Lay-up speed: 9m/min
Number of layers: 19
Laser angle: 25°

Conclusion:

From the picture it can be concluded that in this sample the presence of voids is minimal and a good compaction has been achieved.

uppermost layer

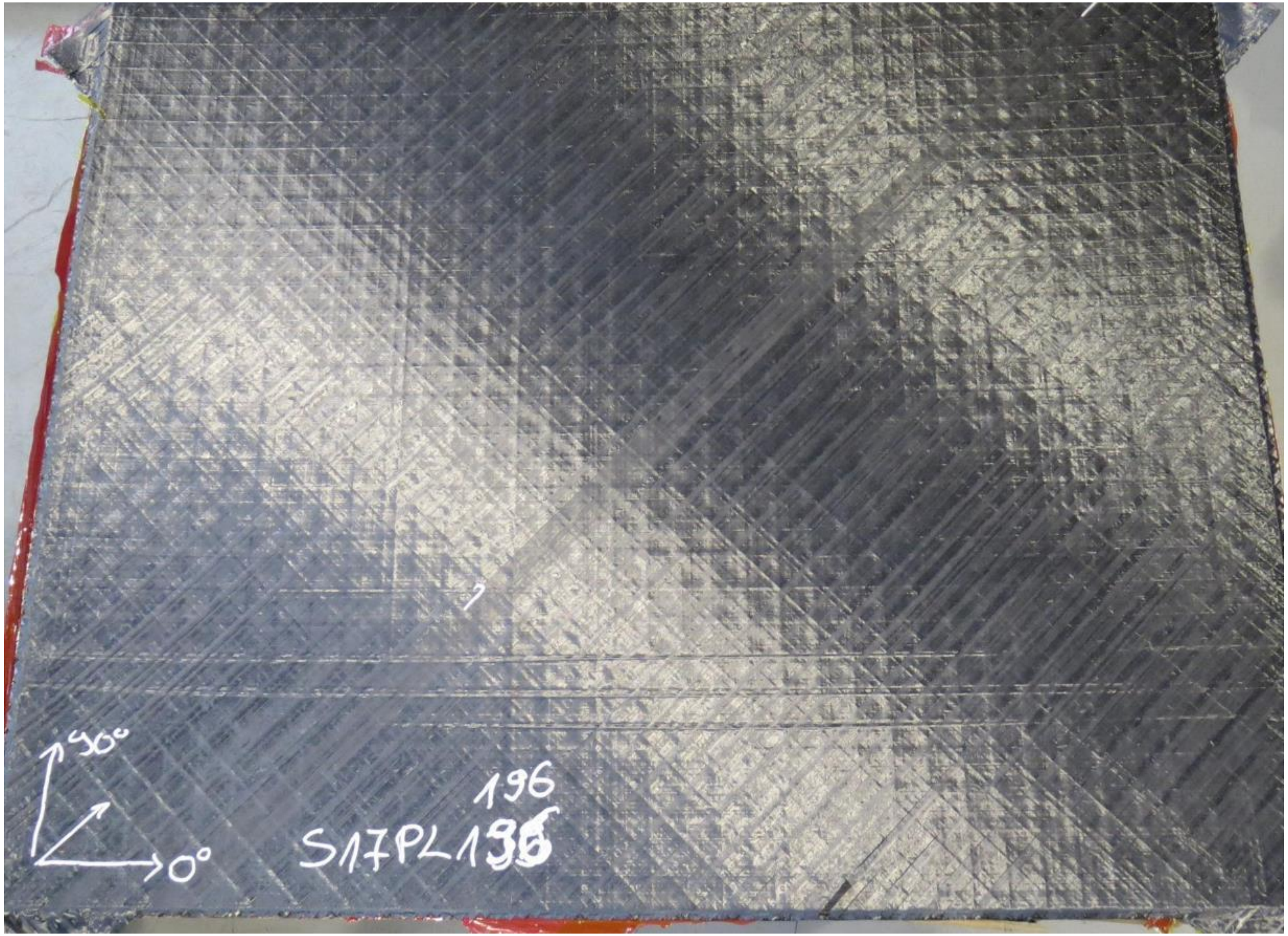


lowermost layer

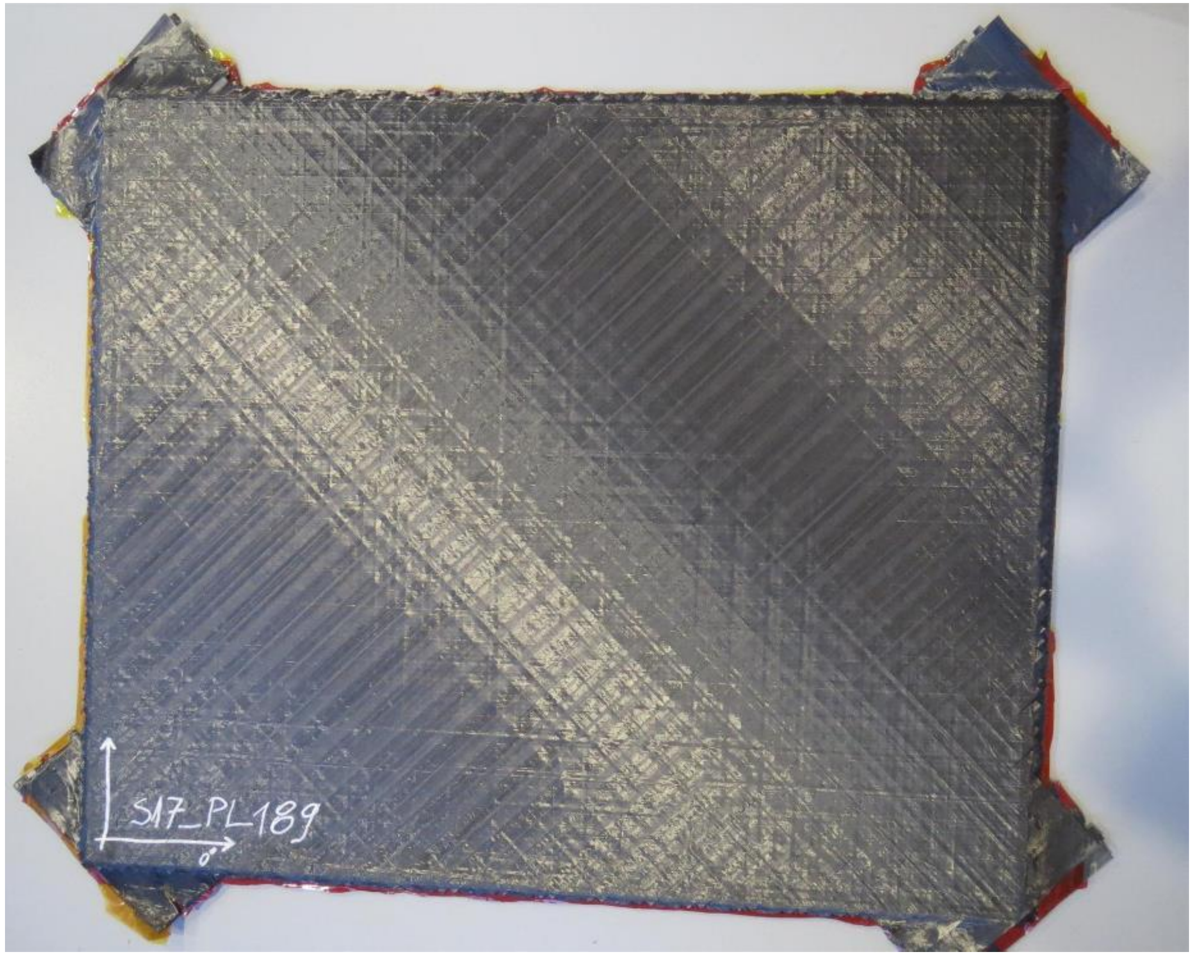
Void percentage: **~2 %**

- 2 Suppliers
- 3 Carbon Fiber matrices from each Supplier: PPS, PEKK and PEEK
- Testing of UD and QI panels:
  - tension, bending, compression, short beam shear / ILSS, voids and crystallinity
- Benchmarked against known carbon-fiber epoxy thermoset results
- Number of layers: 8, 16, 25, 30, 32 and 43 layers
- Varying parameters:
  - Nip-point target temperature based on matrix: 360C, 450C and 460C
  - Table temperature: 60C, 175C and 200C
  - Laser angle at 15.7deg
  - Speed: 6m/min and 10m/min

AFP THERMOPLASTIC PANEL TRIALS CF-PEKK: 32 PLIES QI (LEFT) AND 43 PLIES UD (RIGHT)



AFP THERMOPLASTIC PANEL TRIALS WITH CF-PPS: 32 PLIES QI (LEFT) AND 16 PLIES UD (RIGHT)



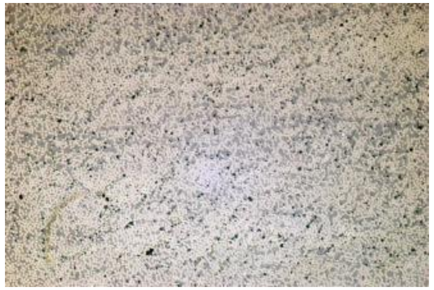
SAMPLE LOW POROSITY LAMINATES WITH PPS/CF

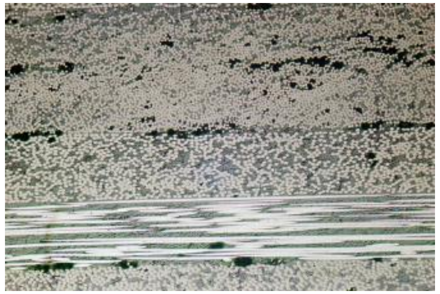
a) UD laminate

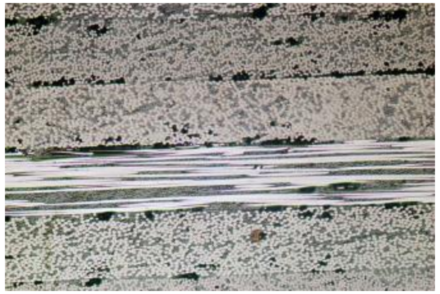
b) QI laminate [45/0/-45/90]

c) QI laminate [45/0/-45/90]

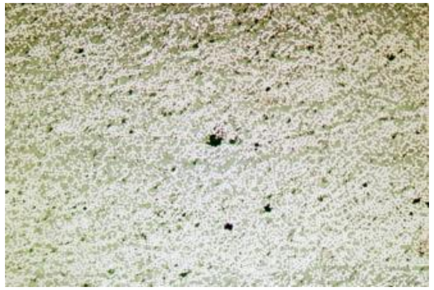
Heated tool 60C

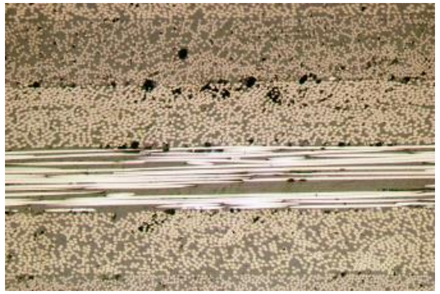


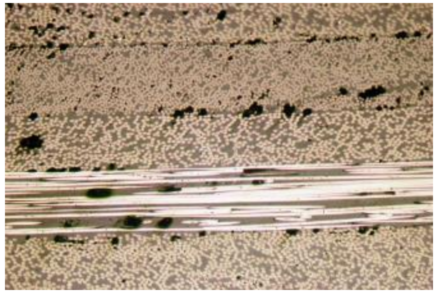


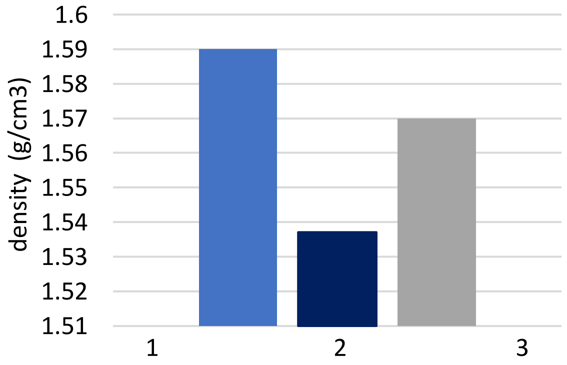


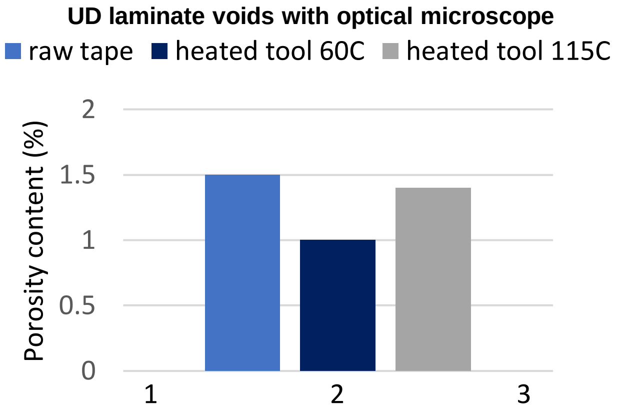
Heated tool 115C









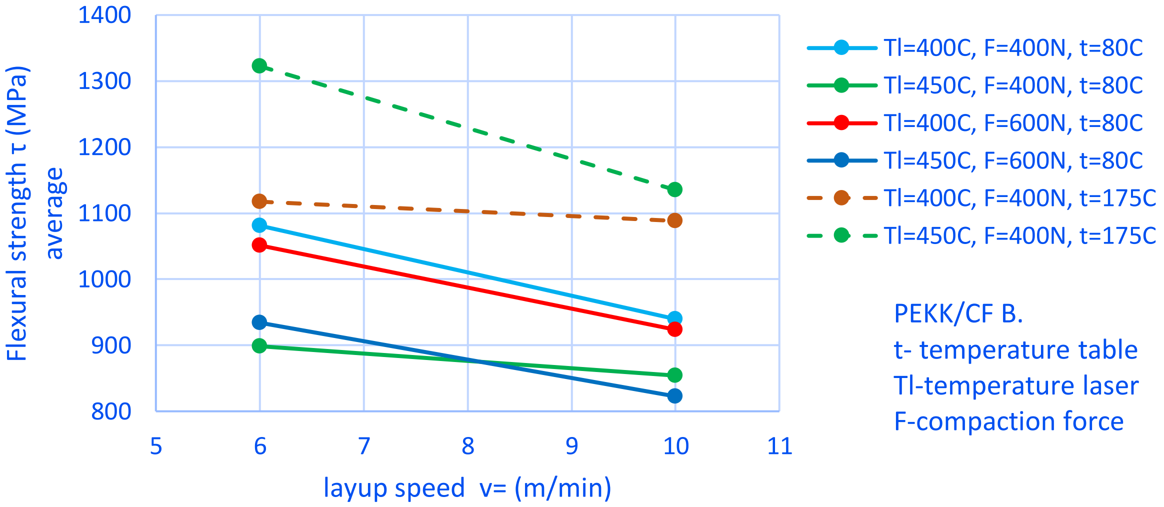


INITIAL EXPERIMENTS: FLEXURAL STRENGTH IMPROVEMENT WITH HEATED TABLE FOR PPS & PEKK

Test for PEKK/CF

Input parameters Variable DOE 2^4=16 sample:
- temperature of table 80-175C
- temperature of laser 400-450C
- compaction force 400-600N
- Layup speed 6-10m/min

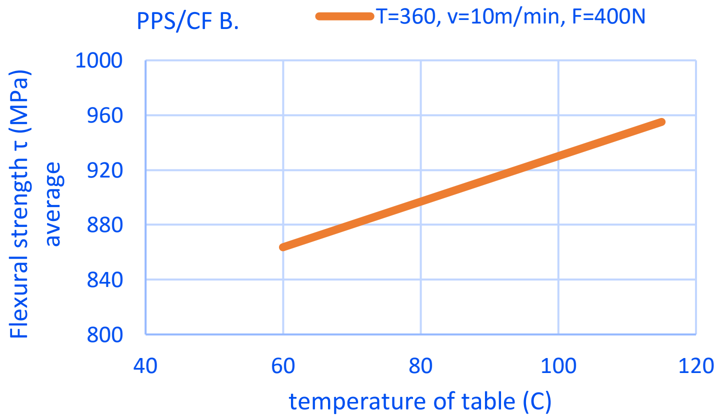
Lower speed,
High table temp
=> INCREASE strength
BUT if low table temp,
increase FORCE to
compensate for low speed

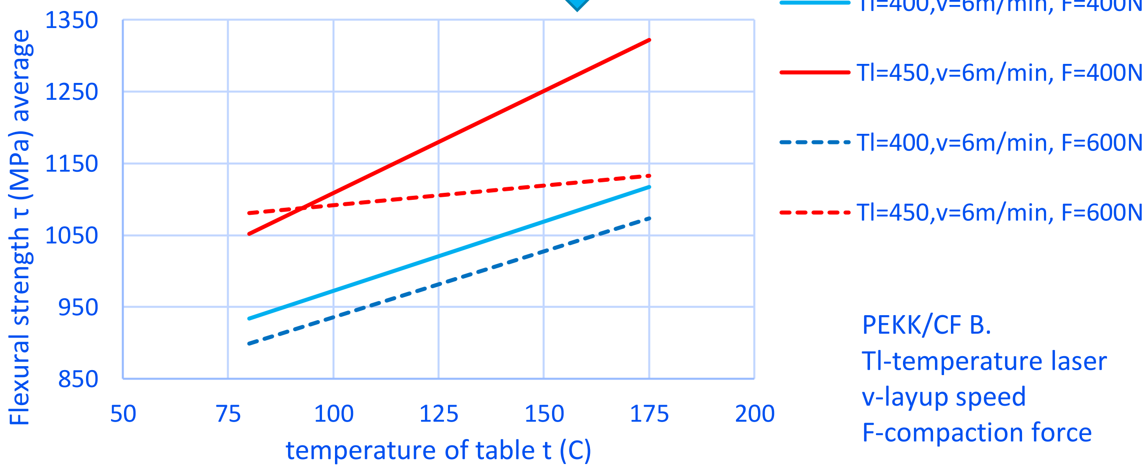


Output parameters
Mechanical properties
- 3pbt

Results – analysis

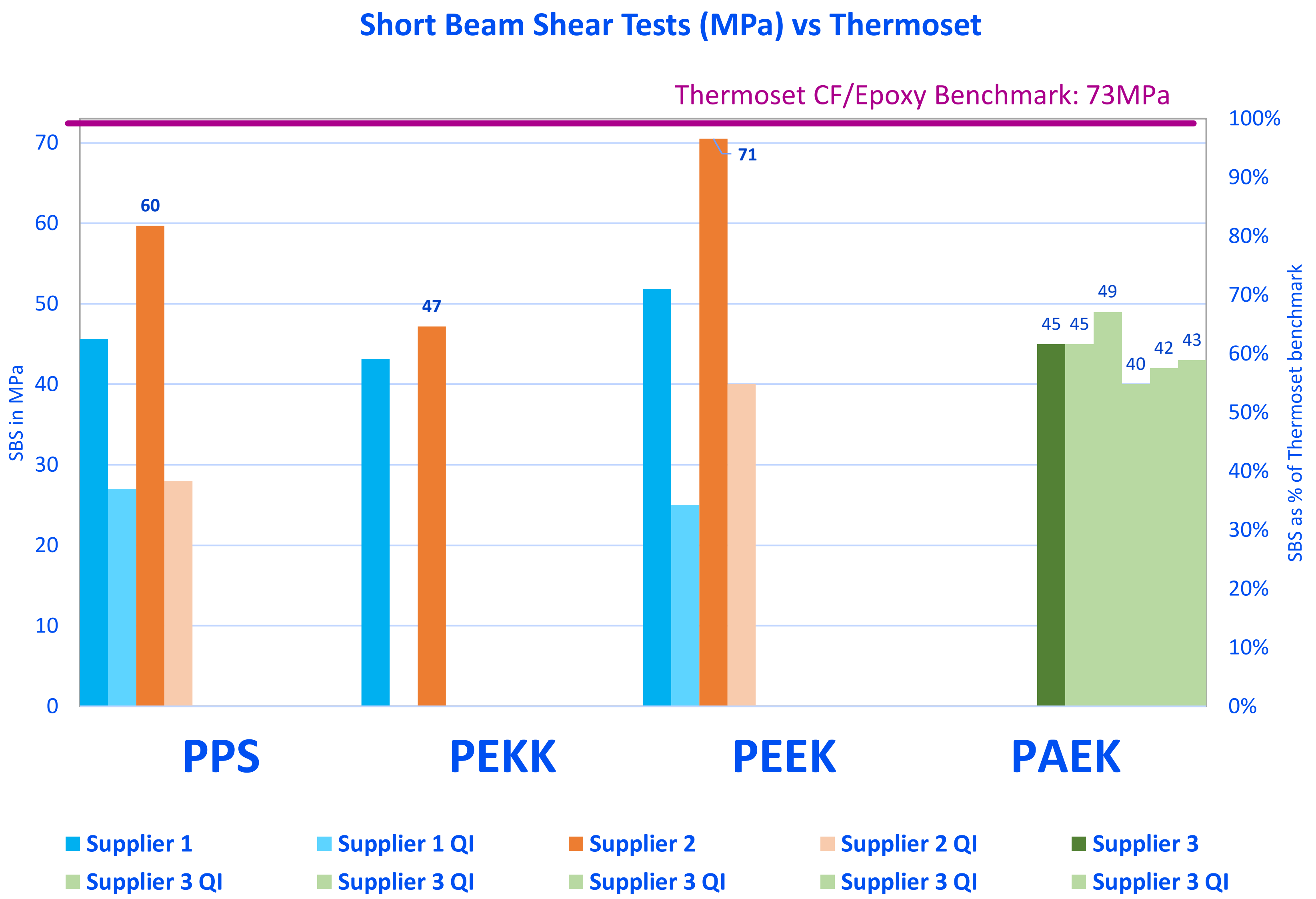
Test for PPS/CF prepreg:
Temperature of table Increases flexural strength



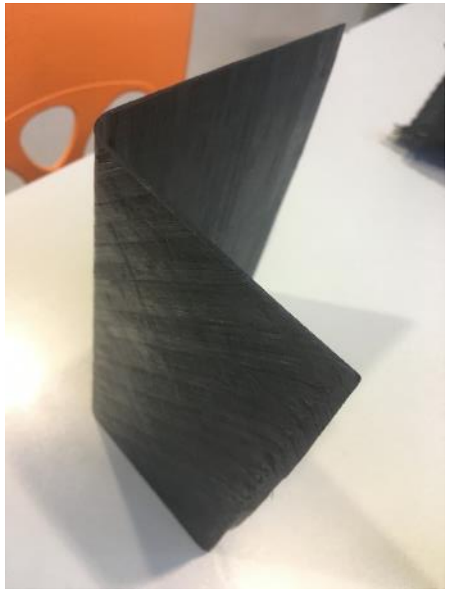


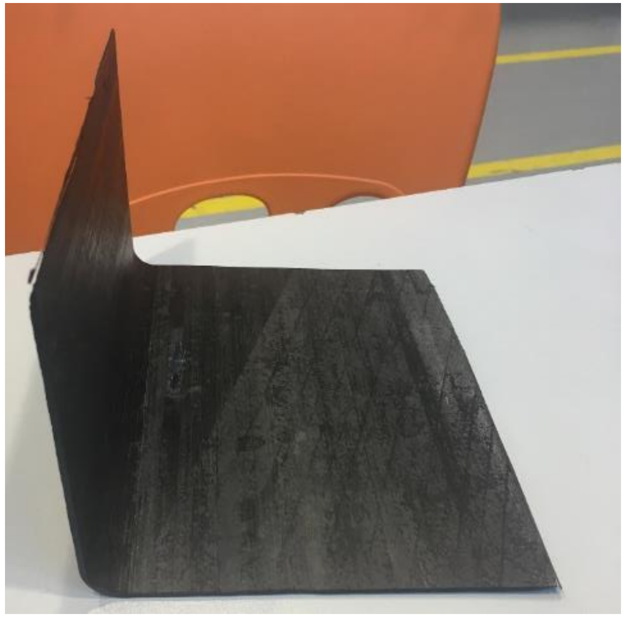
SHORT BEAM SHEAR TEST VS THERMOSET BENCHMARK: SUPPLIER QUALITY AND PEEK MATRIX PROVIDE EXCELLENT RESULTS REACHING 97% OF THERMOSET

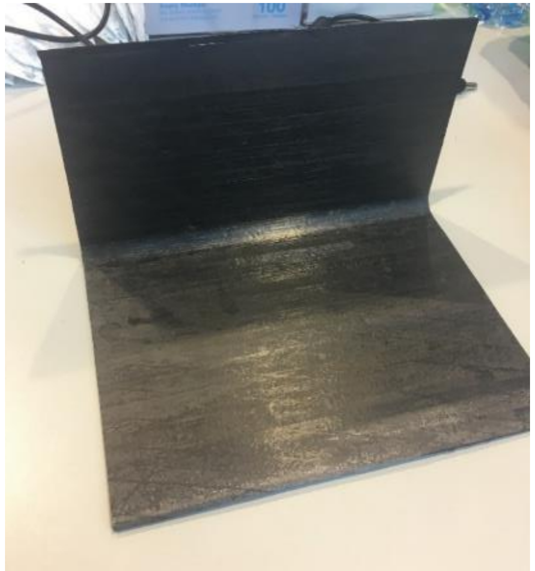
- In-situ consolidated AFP samples. No additional treatment
- Ability to reach >80% of Thermoset benchmark
- Obvious differences between Supplier 2 and Supplier 1 in the same matrices
- PEEK clearly better results than PPS or PEKK, reaching 97% of benchmark
- UD 43 layers decidedly better than QI 32 layers
- Older PAEK tests show fairly consistent results, but with higher porosity
- PAEK vs others not apples to apples comparison, but a good start nonetheless
- **Customer chose Supplier 2 PEEK for large curved airplane part based on these and other tests**

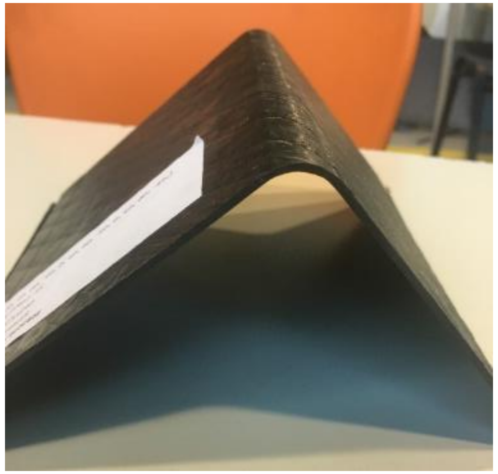


L-SHAPED THERMOPLASTIC SAMPLES, AFP 4-TOW, VERY GOOD COMPACTION AT EDGE



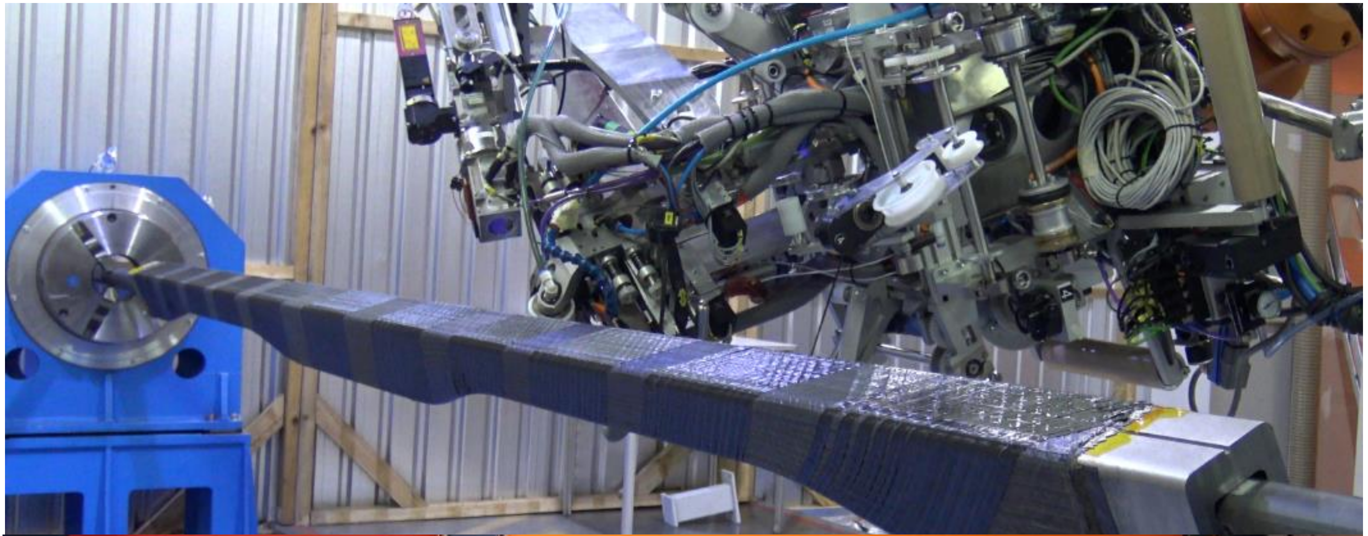






STEERING WITH THERMOPLASTIC, SAMPLES, AFP 4-TOW: 400mm DIAMETER AT 10m/min

TRANSFER OF THESE EXPERIENCES TO COMPLEX PARTS



Clean Sky 2

The work presented on this slide is part of a Clean Sky 2 funded project under LPA. Photos courtesy Mikrosam

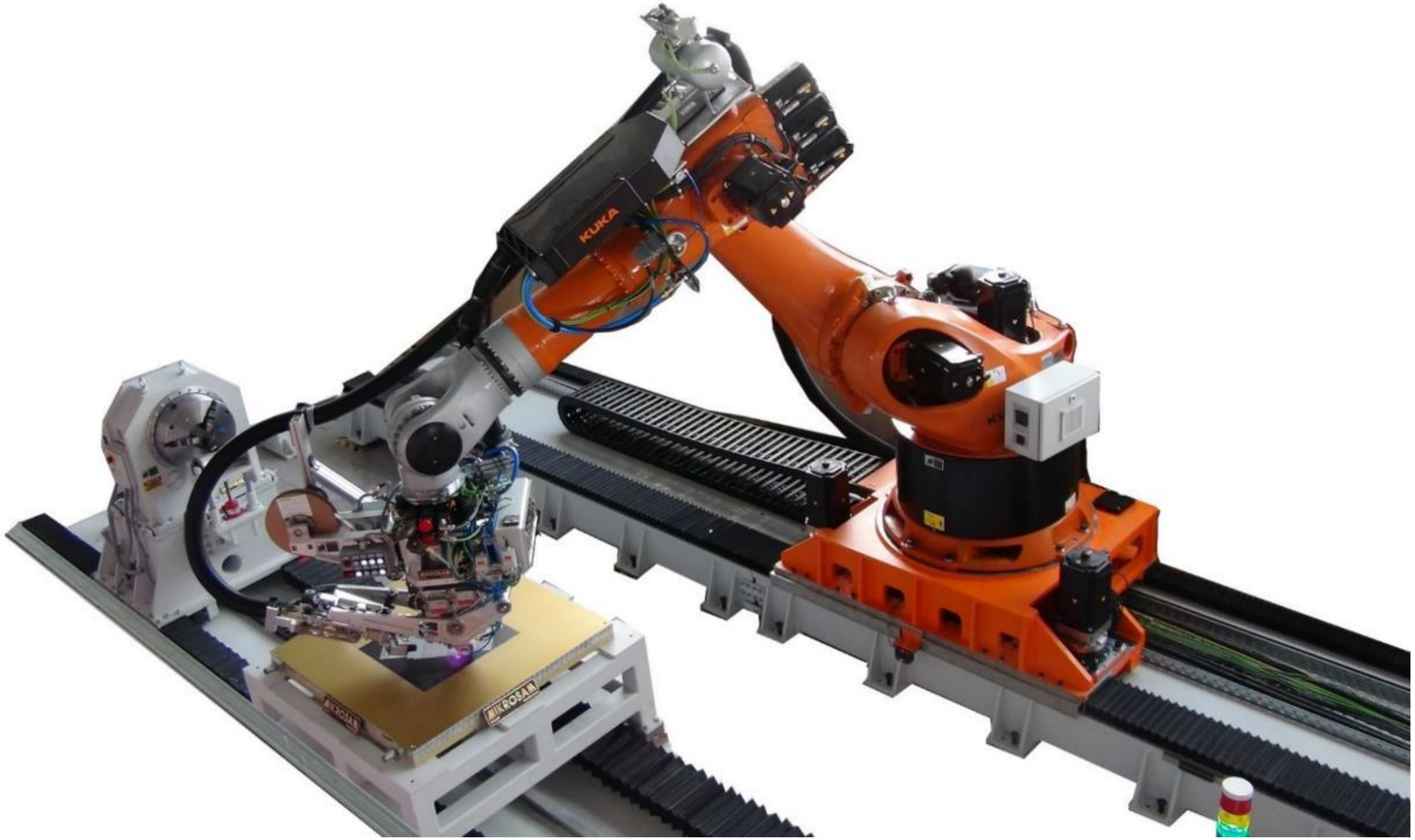
TRANSFER OF THESE EXPERIENCES TO COMPLEX PARTS

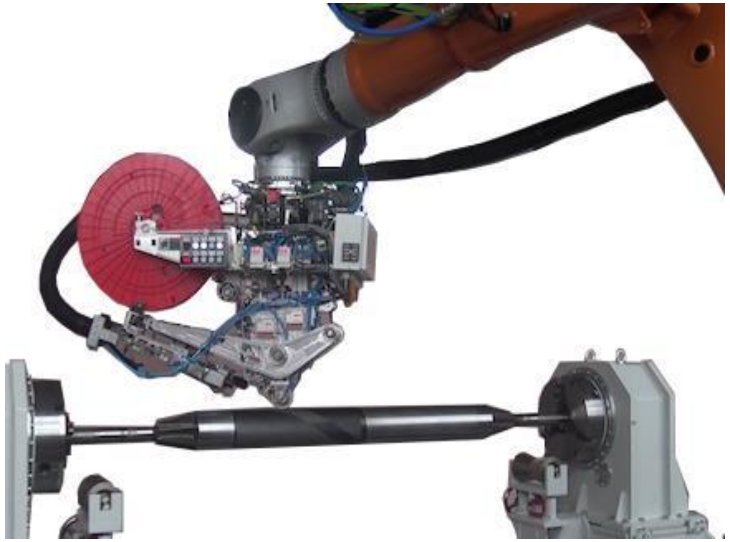
The work presented on this slide is part of a Clean Sky 2 funded project under LPA.
Photo courtesy GKN Fokker

KEY TAKEAWAYS BEFORE PROCEEDING TO DUAL-ROBOT AFP

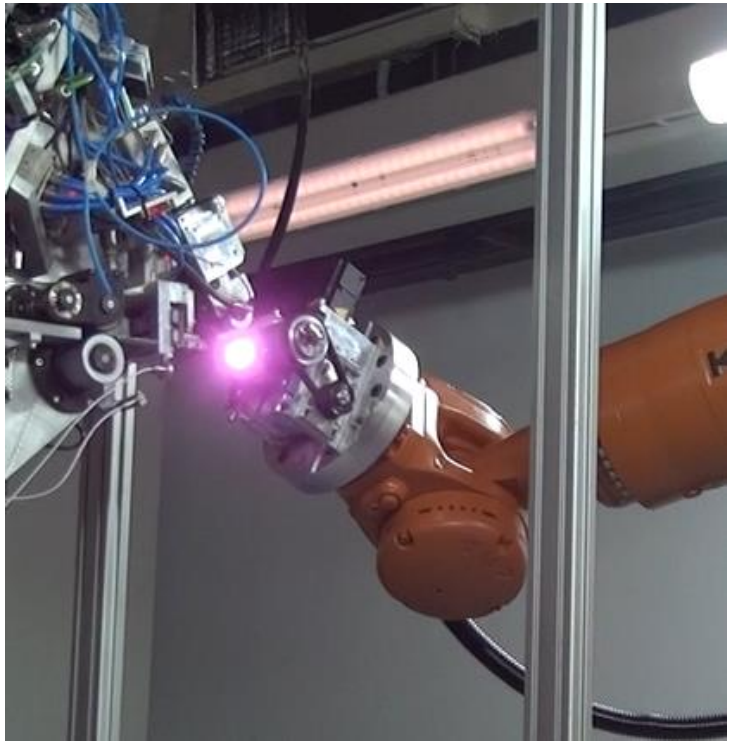
- Raw material quality variation and supplier is a big starting factor
- Flat panel and material trials are only the beginning
- Input parameters to account for flat and complex shapes:
  - laser temperature at specific point of course, layer, angle, and shape,
  - tool or ambient temperature,
  - laser angle,
  - compaction force,
  - speed of layup, and speed of cooling, etc.
- Thermal models for layup need to differentiate between UD and QI, complex shapes, courses, layers, angles, etc.
- AFP Unit needs all flexibility to account for multiple parameters which dictate final outcome
- Transitioning from flat panels to complex shapes is not always direct (ie, heating a large tool not always possible)
- Annealing can be your friend, try to make it cost-effective
- Which of these experiences can you transfer into tool-less layup?

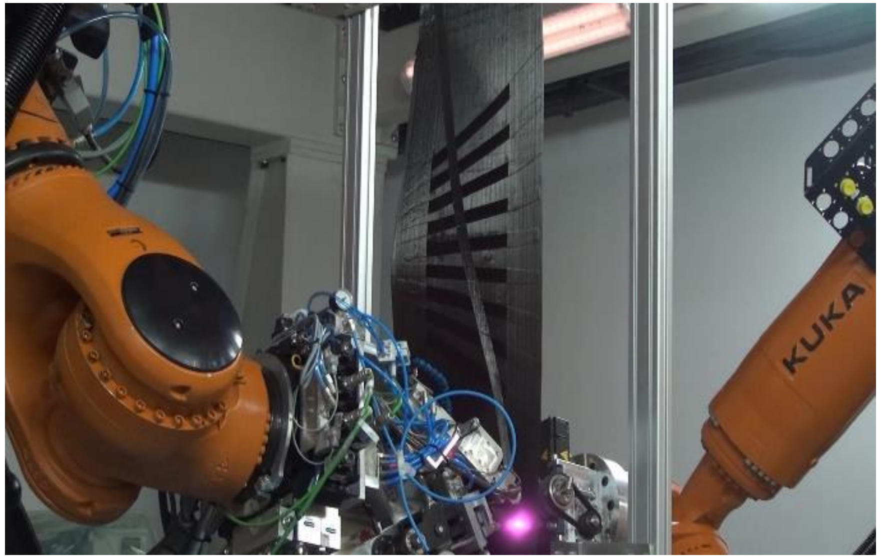
HOW DO WE TURN THIS EXPERIENCE INTO TOOL-LESS?

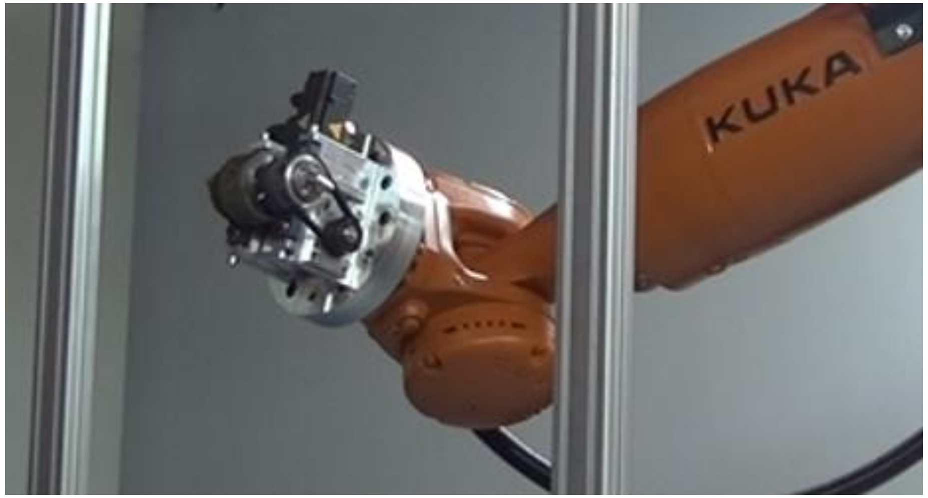


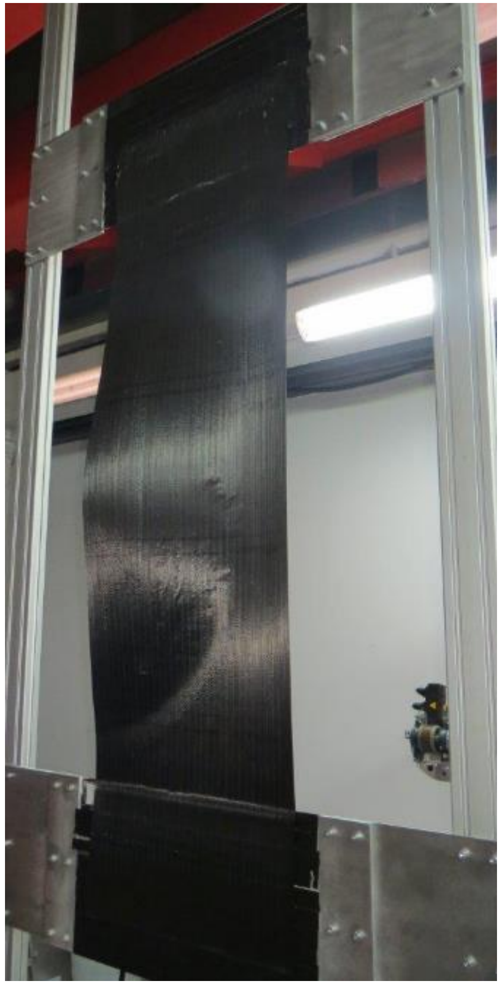


HOW DO WE GET TO HERE?





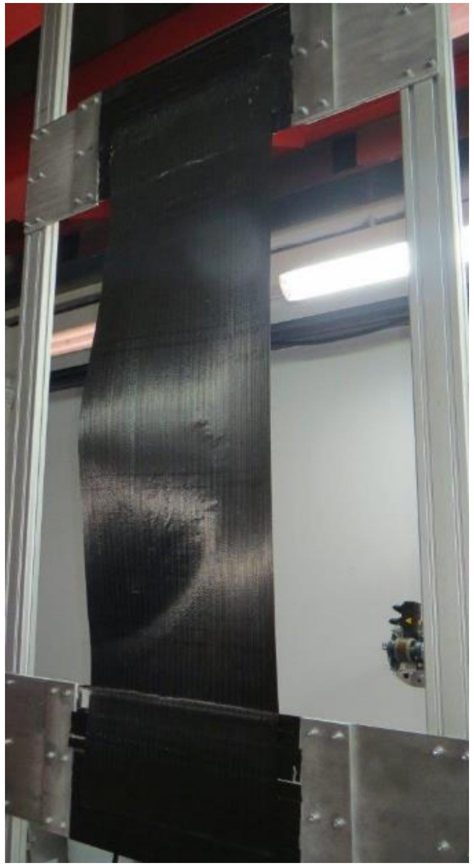


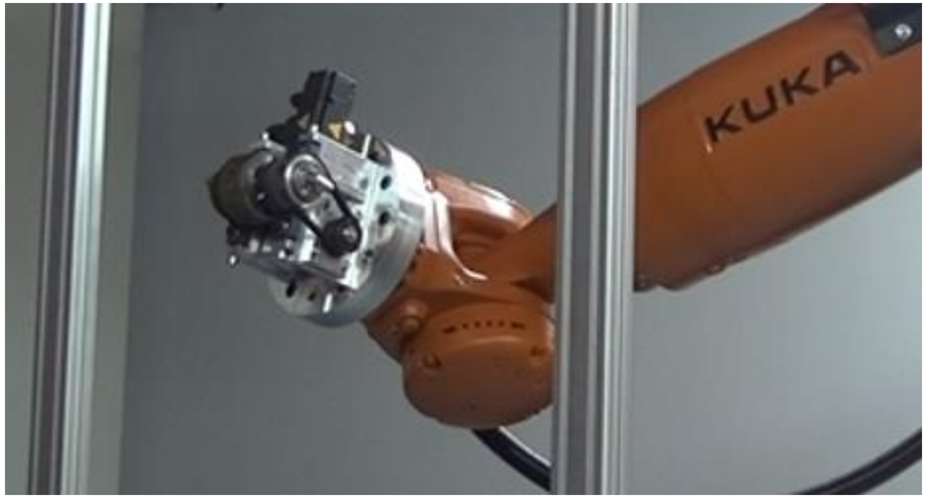


KEY CHALLENGES TO OVERCOME FOR TOOL-LESS AFP

- Connecting and synchronizing two robots for dynamic movement in 3D space
- Calibration of the individual movements of both robots for accuracy and repeatability
- Programming: improvements to MikroPlace to support tool-less part design
- Technology development of the layup process
- Can you transfer experiences from single Robot AFP (flat or curved mandrels) to tool-less?

- Design a tool head – Support Head on opposite robot
- Ensure parameters of flat tool can be met dynamically
- Roller movement – controlled and synchronized, or uncontrolled
- Room temperature or chilled/heated
- Counter-pressure or support only
- Volume and size of roller and Support Head
- Fighting gravity with Support Frame
- AFP Head (Single tow AFP) considerations
  - Flexible compaction,
  - Laser Angle adjustments,
  - Flexible tension

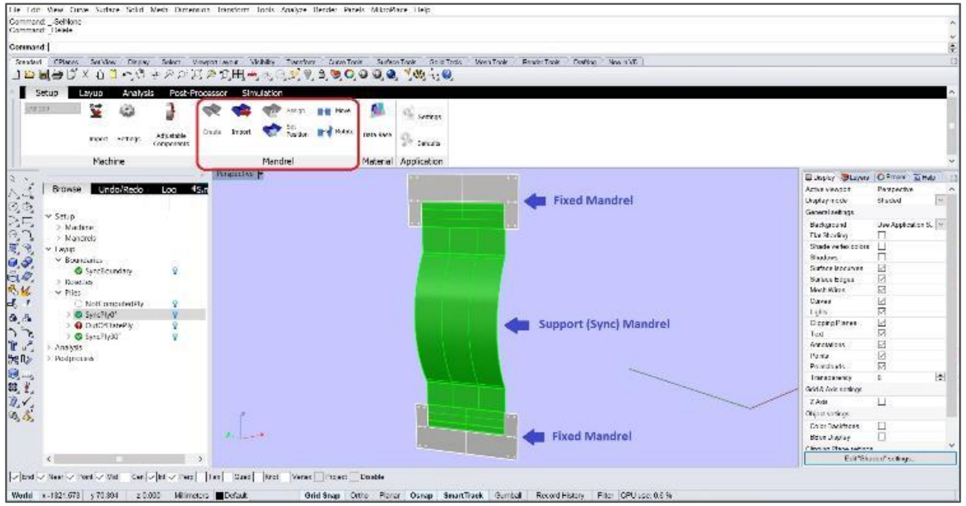


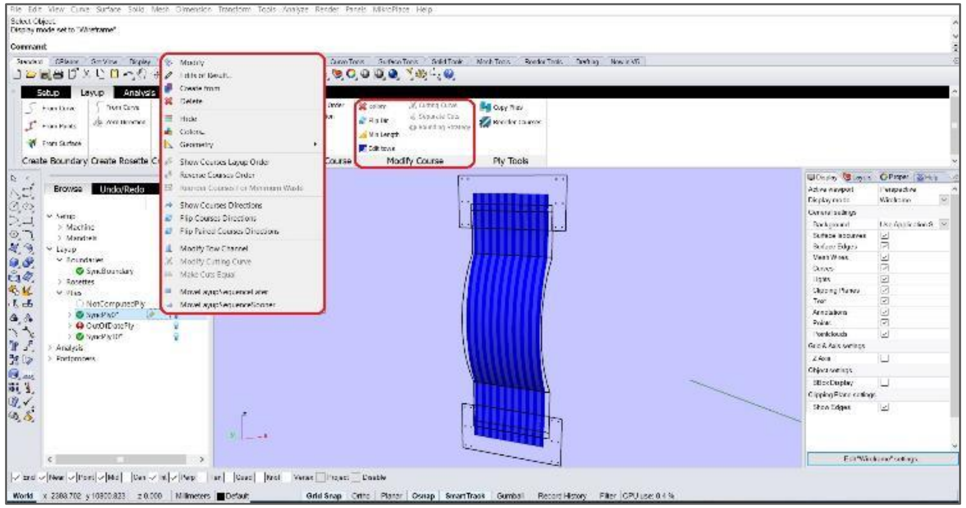


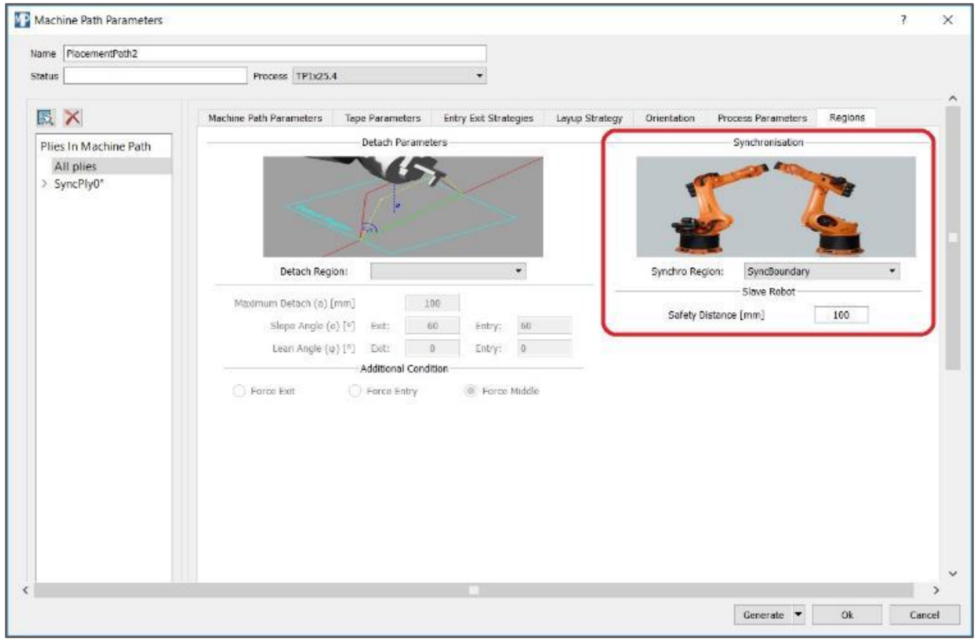
Electrical & Programming Issues to Consider and Solve

- Develop inverse kinematics of the robot and synchronize the volume compensation algorithm for accuracy and repeatability of both robots
- Multiple Tool Control Point probing
- Create a Robot dance and axis interpolation

MIKROPLACE – DUAL ROBOT CAPABILITIES NEEDED







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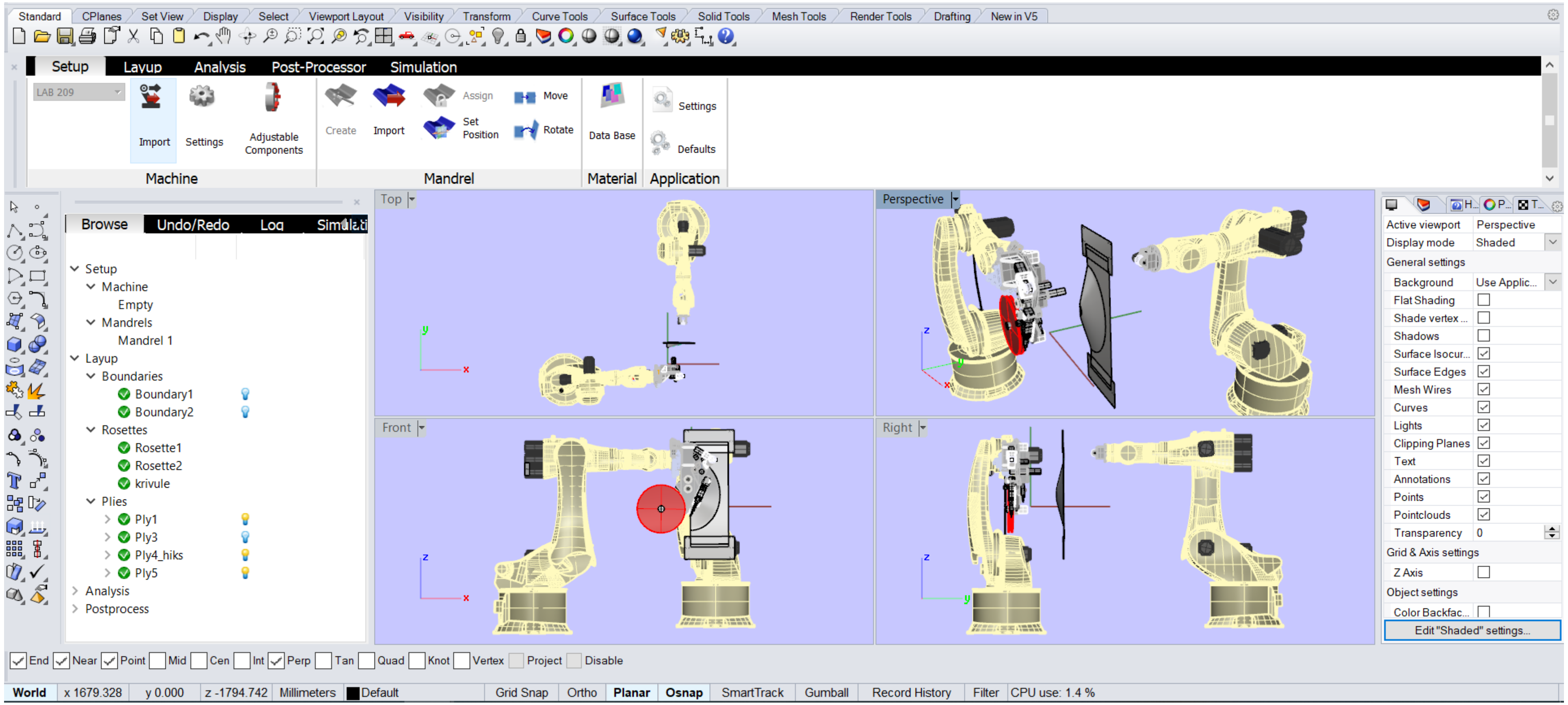
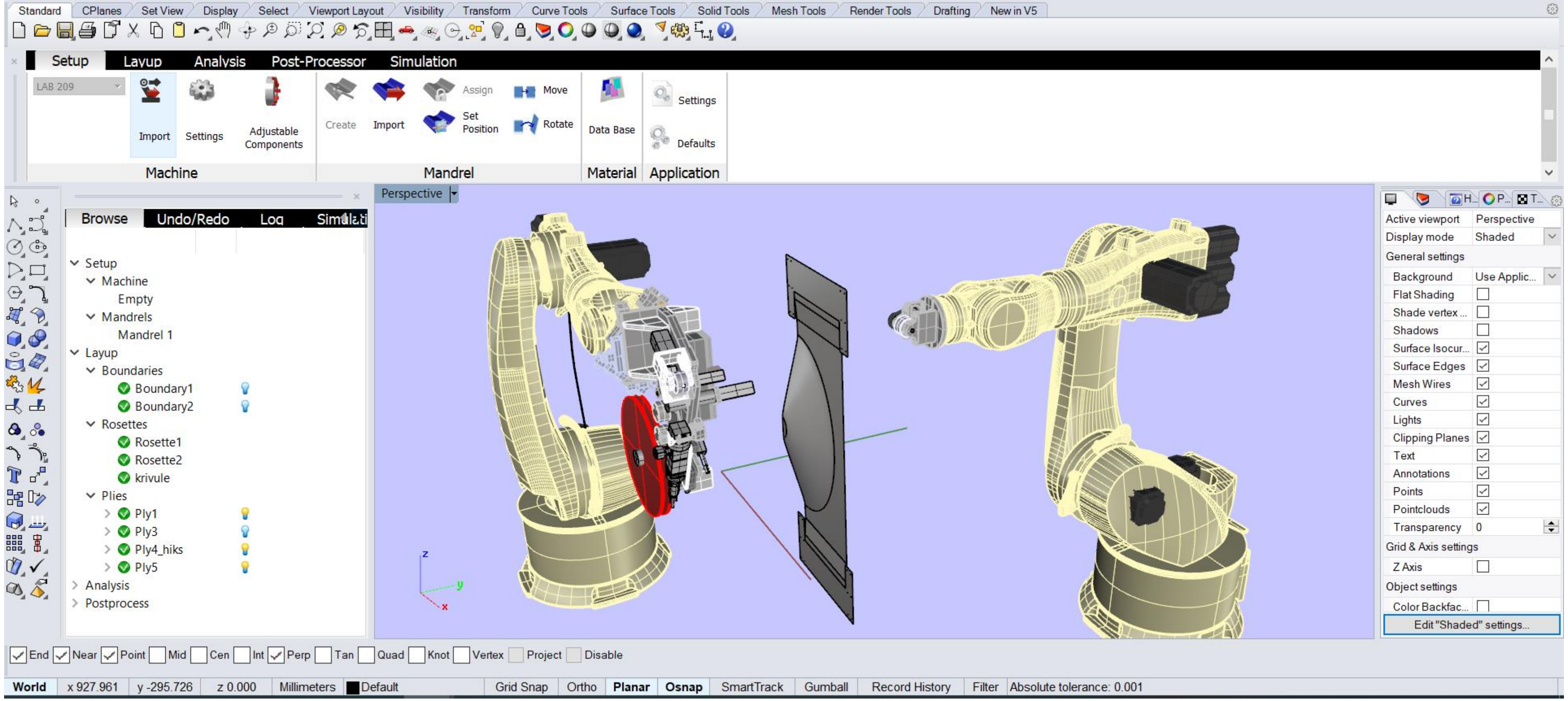


MIKROPLACE – DUAL ROBOT CAPABILITIES NEEDED



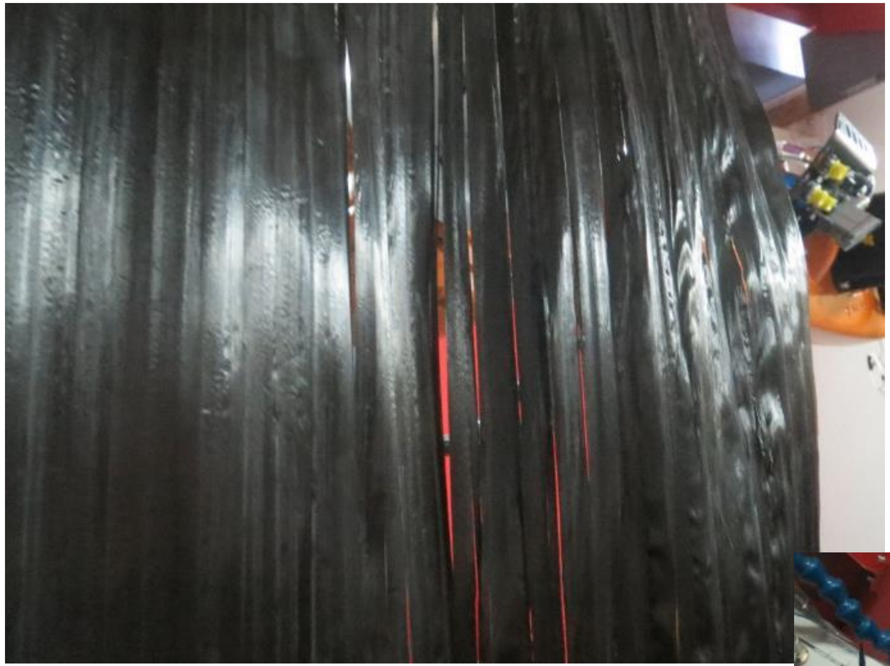
MIKROPLACE – DUAL ROBOT CAPABILITIES NEEDED

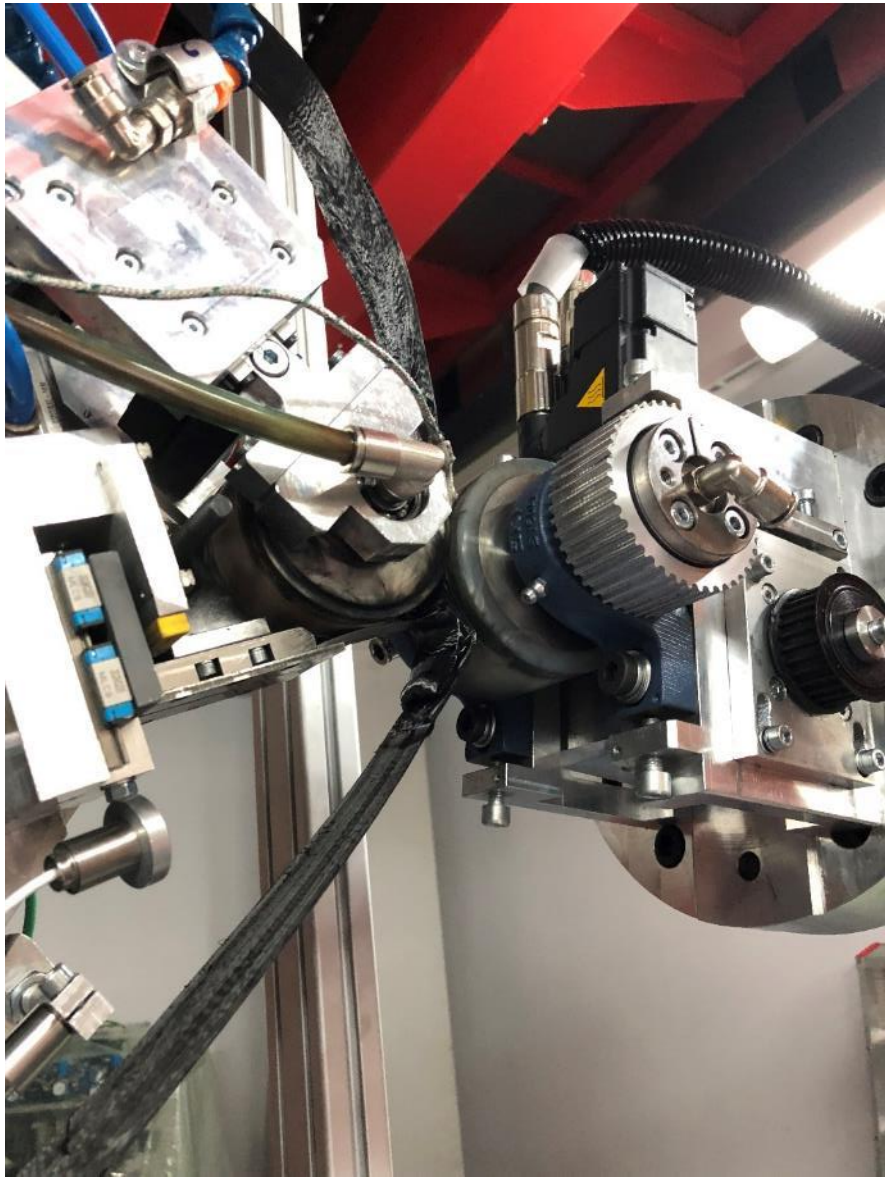
Create Synchronization Boundary for Dual Robot Layup:
- From Curve - design and select curves for boundary
- From Points - create automatic curve on surface by points
- From Surface - design and select surface for boundary

Create Layup for Dual Robot by using:
- Several layup strategies: constant angle, geodesic curve, parallel path, courses from curves etc.
- Boundaries for ply and initial curves
- Starting point of each ply
- Steering, Fitting, Dropping, Stagger strategies
- Rosette strategies
- And many more options and strategies…

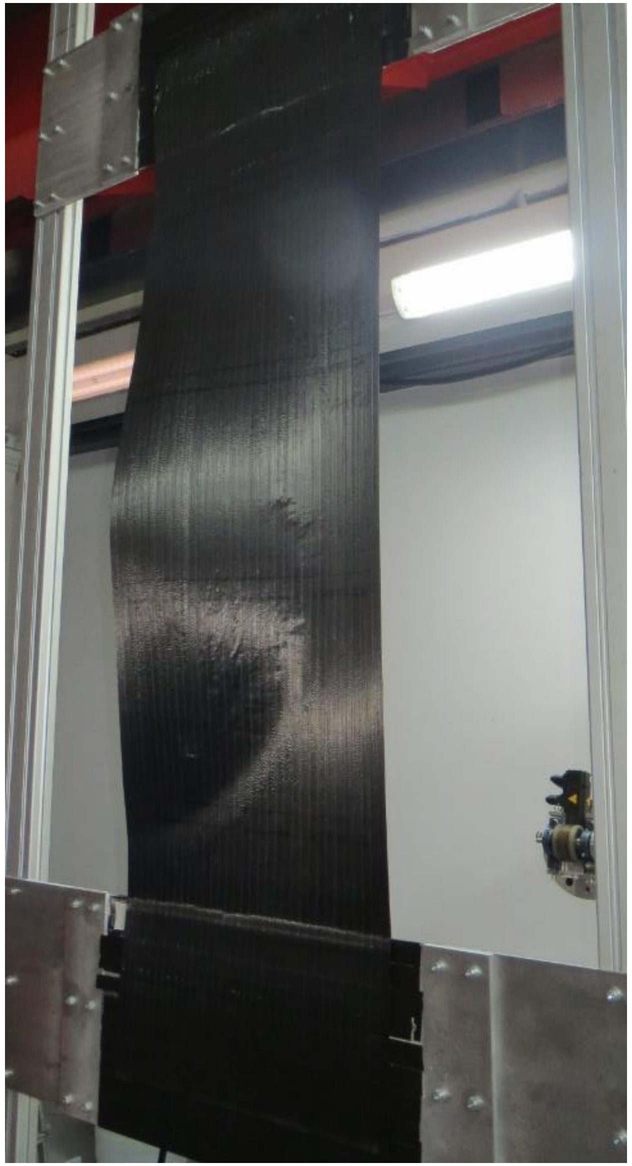
Create Machine Path for Dual Robot by using:
- Free Head path strategies (safety plane, offset mandrel, custom envelope, head orientation)
- Lead In/Out, Mandrel movement and waste material strategies
- Tape and Process parameters
- Layup speed and Mandrel Entry/Exit strategies
- Special Regions (Synchro Region for Dual Robot)

CHALLENGES FOR TOOL-LESS AFP IMPLEMENTATION

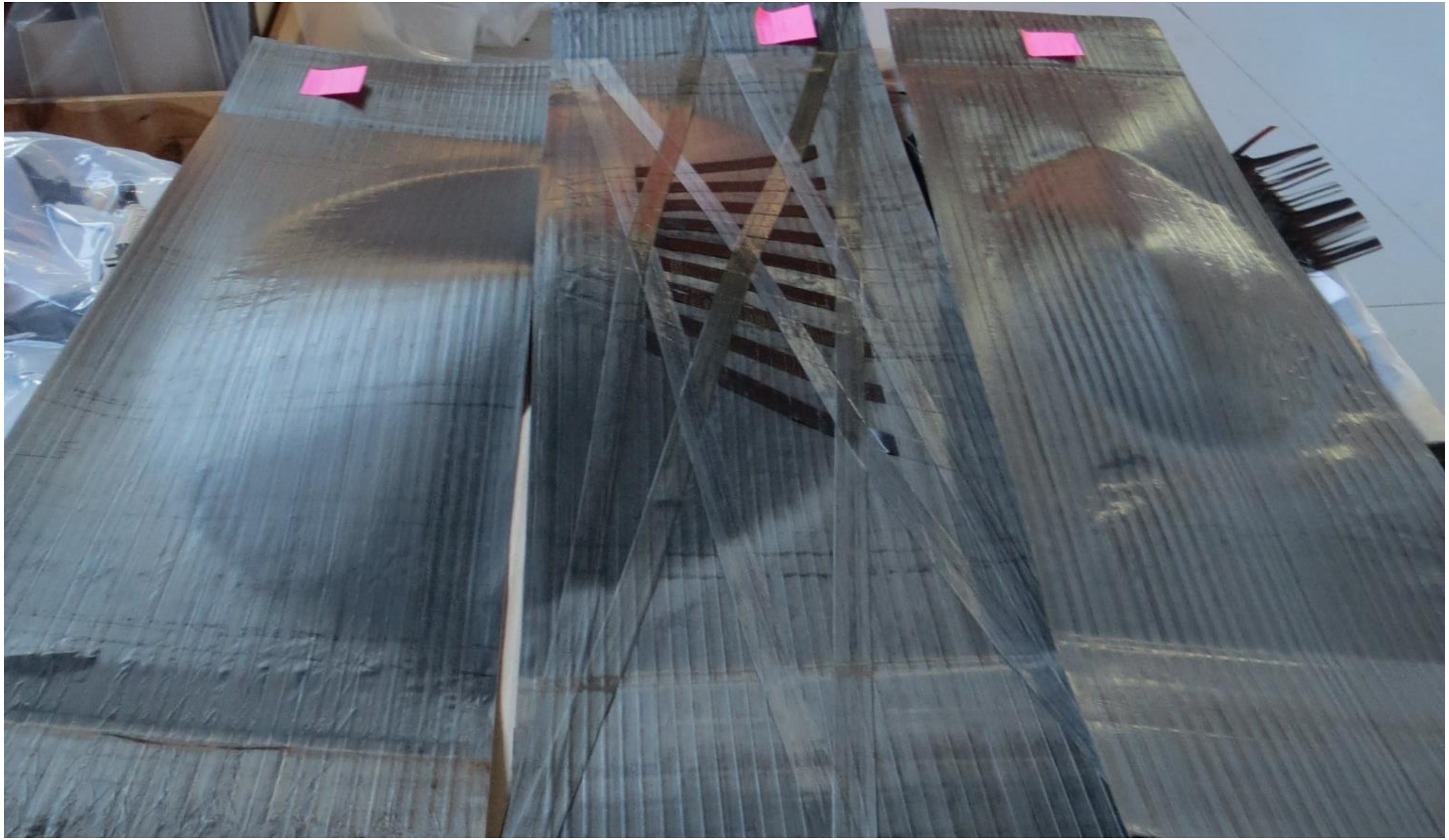




CHALLENGES FOR TOOL-LESS AFP IMPLEMENTATION



THERMOPLASTIC PRODUCTS MANUFACTURED WITH MIKROSAM'S DUAL-ROBOT AFP TECHNOLOGY

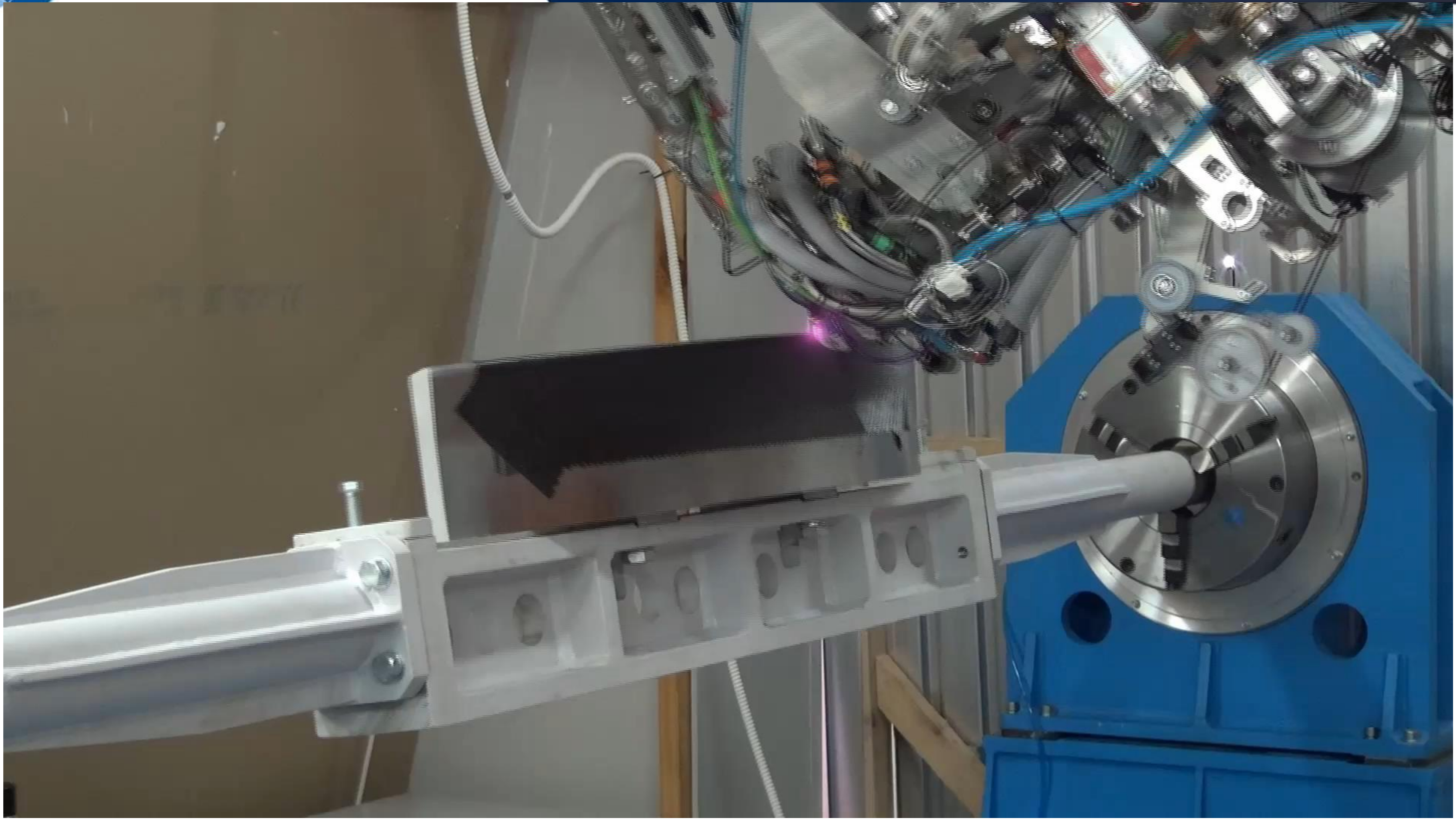


TOOL-LESS AFP: CONCLUSIONS

- Robot synchronization is key to successful process development
- Materials tried: PEEK and PEKK with different thickness. Thickness of material had negative impact on layup stability (counter-intuitive)
- Programming must account for flexible parameters
- Initial courses need to be flat with 20-40% of overlaps
- Tension needs to be much higher on initial layers
- Layer and course build-up is progressive and gradual, with alternating overlaps, temperature and tension adjustments
- Flat panel parameters don’t translate to tool-less layup
- Initial layers build a supporting area for further layup of material
- 3D Deviation of design to layup ~5% area and volume estimates

NEXT STEPS IN TOOL-LESS

- Improve curvature handling of 3D layup
- Reduce the size of the cell with smaller robot, head and support
- Introduce 3rd supporting robot w/o Supporting Frame
- Continue testing material, shape and process parameters for desired characteristics



- Customers
- Mikrosam's Engineering Team

- NASA's Pat Cosgrove & Robert Bryant
- General Atomics' John Geriguis & Adam Jones
- Composite Automation's John Melilli

MIKROSAM: INNOVATIVE COMPOSITES MANUFACTURING SOLUTIONS

Since 1990

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