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Finite Element Simulation of Delamination Processes when Side Milling the Edges of Cross-Ply CFRP

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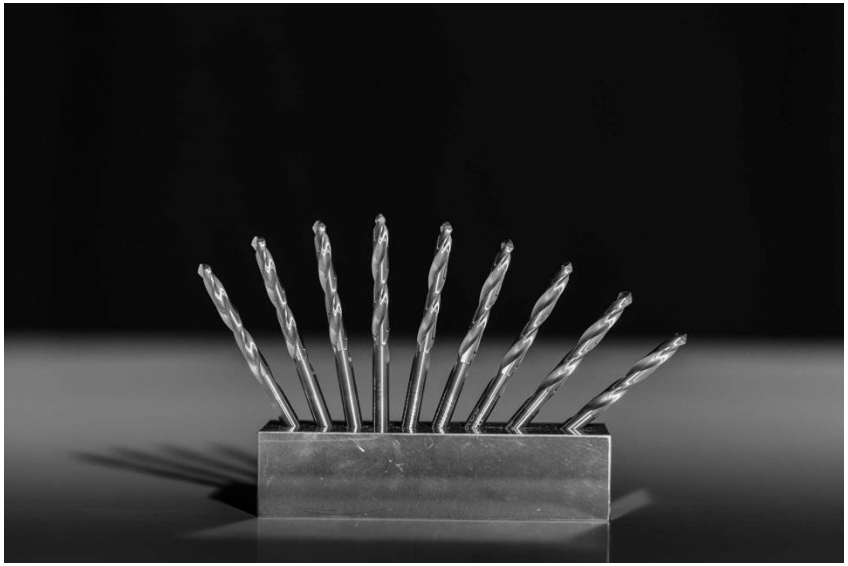

Finite Element Simulation of Delamination Processes when Side Milling the Edges of Cross-Ply CFRP

Agenda

- Simulation of machining processes
- Machining of FRP components
- Experimental and simulation setups
- Results and discussion
- Conclusions and outlook

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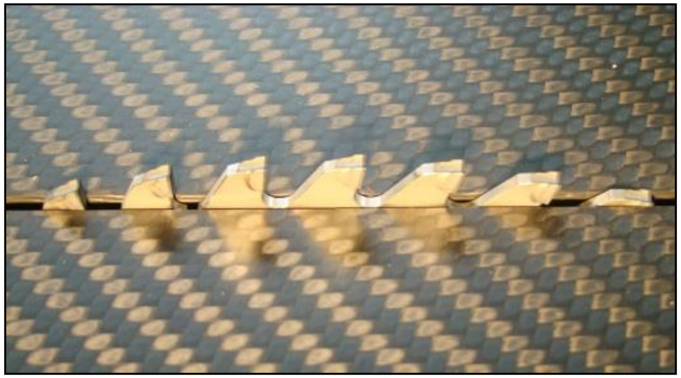
Simulation of machining processes
Processes and variables

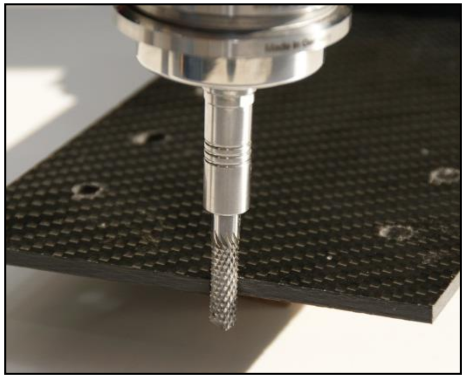
Machining processes

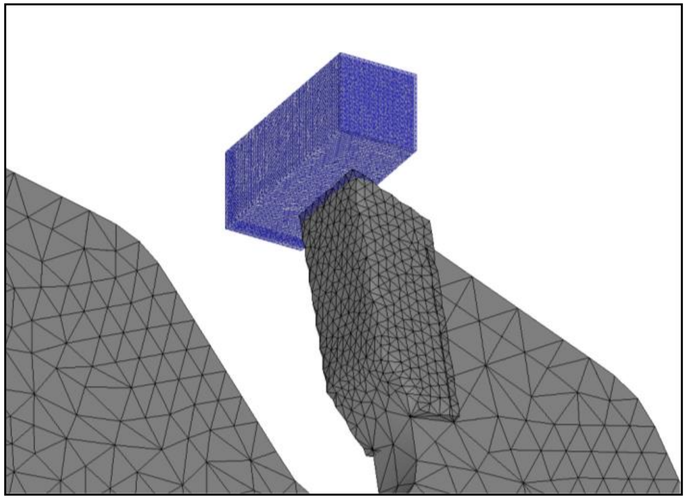
- Turning
- Drilling
- Milling
- Sawing

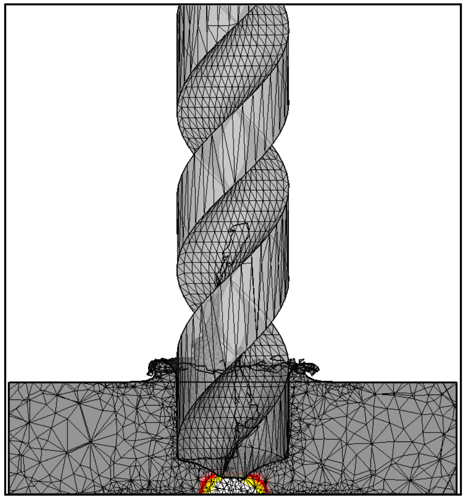
Output values

- Cutting forces
- Temperature
- Stress
- Strain
- Chip formation







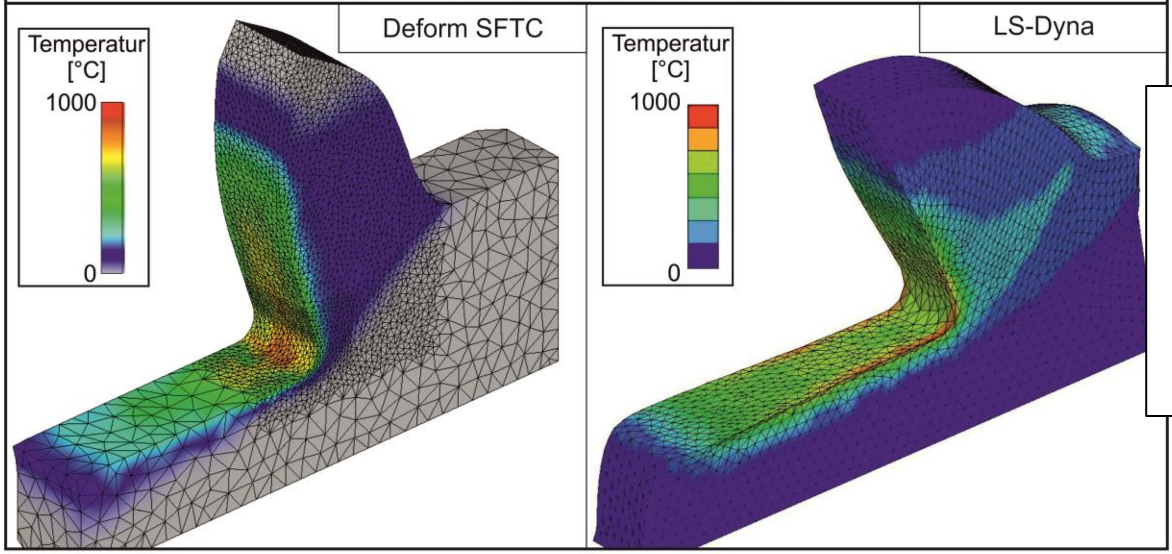


Source: Fraunhofer IPA, 2014

Simulation of machining processes
Objectives

- Determination of the relationships between:
  - cutting geometries and operational parameters
  - stress, strain and temperature variables in the process

Software for the simulation of machining operations



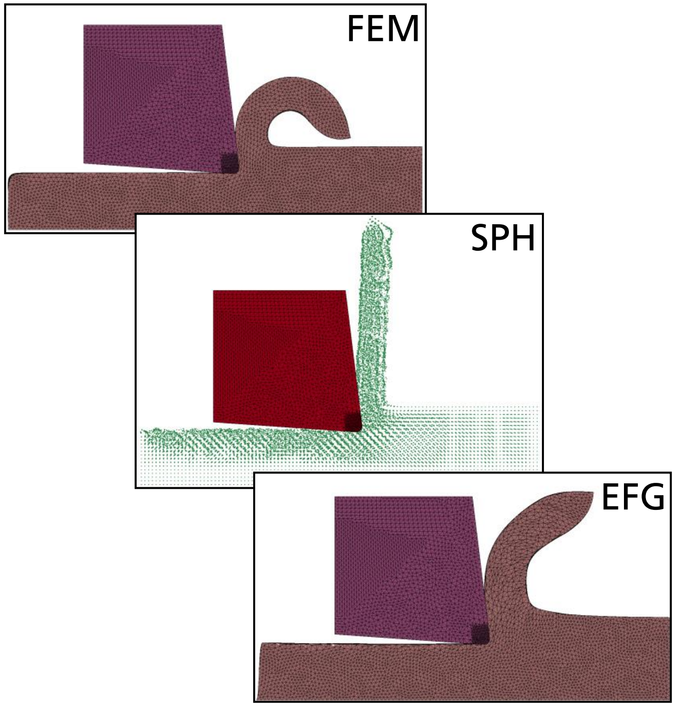
Approximation and close analysis of the high thermo-mechanical loading conditions inside the process

Source: Fraunhofer, 2013

- Tool development through virtual experimentation

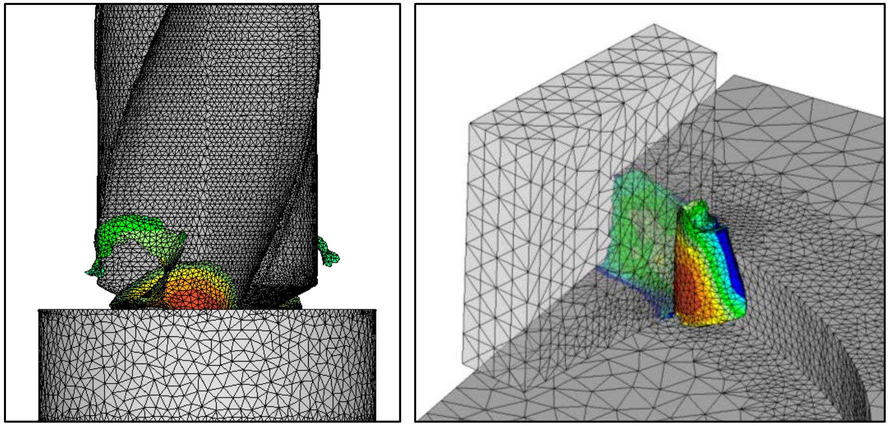
Simulation of machining processes
Numerical methods and operations

- Different numerical approaches:
  - Finite element method (FEM)
  - Smoothed particle-hydrodynamics (SPH)
  - Element-Free-Galerkin method (EFG)



Source: Fraunhofer IPA, 2014

- Machining operations:



Source: Fraunhofer IPA, 2013

Simulation of machining processes

Basic theory and requirements of numerical simulations

Characteristics of machining processes

- Contact and interaction between several bodies
- High dynamic (e.g. v_c > 1 m/s for drilling in thermoplastic material)
- High plastic deformation ($0.5 > \varepsilon > 5$)
- Material separation takes place

Setting requirements for the simulation

Models of material $k_{f(\varepsilon, \dot{\varepsilon}, T)}$

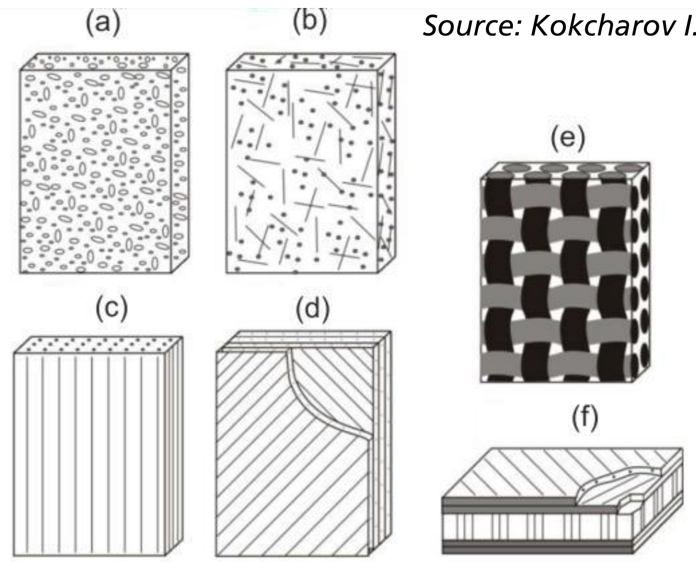
- High deformation (ε)
- Effects of strain rate ($\dot{\varepsilon}$)
- Effects of temperature (T)

Material separation methods

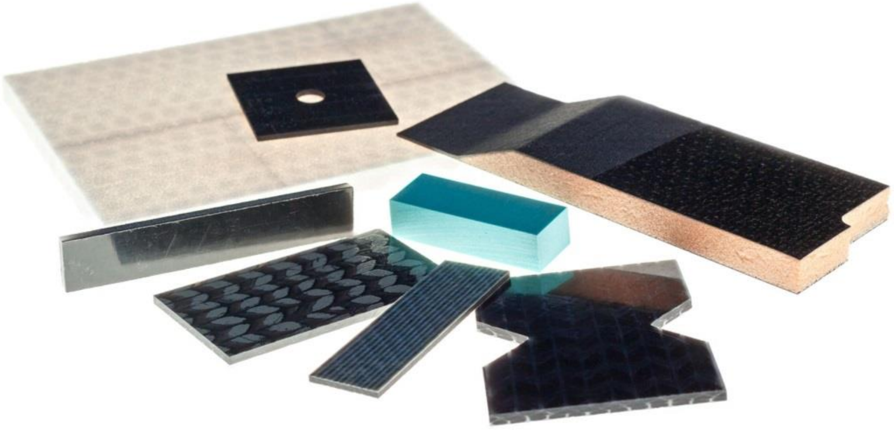
- Node separation
- Elements deletion
- Remeshing
- Mesh-free methods

Machining of fiber reinforced materials
Fiber reinforced polymers (FRP) and composite materials

Source: Kokcharov I., 2013



Source: Fraunhofer, 2013

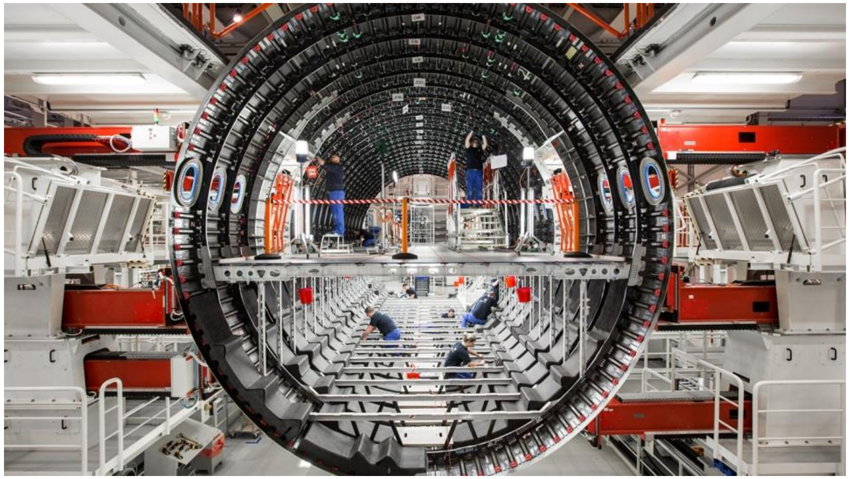


a. Composite reinforced by particle
b. Composite reinforced by chopped strands
c. Unidirectional composite
d. Laminates
e. Fiber reinforced composite
f. Honeycomb composite

The purpose of combining and reinforcing materials is to provide strength and stiffness in lighter structures.

Machining of fiber reinforced materials
Applications of lightweight structures

Source: BMW Group, 2016



Source: CFK-Valley, 2016

Source: Acciona Windpower, 2016

Source: Karl Mayer GmbH, 2016

Source: Münich Composites GmbH, 2016

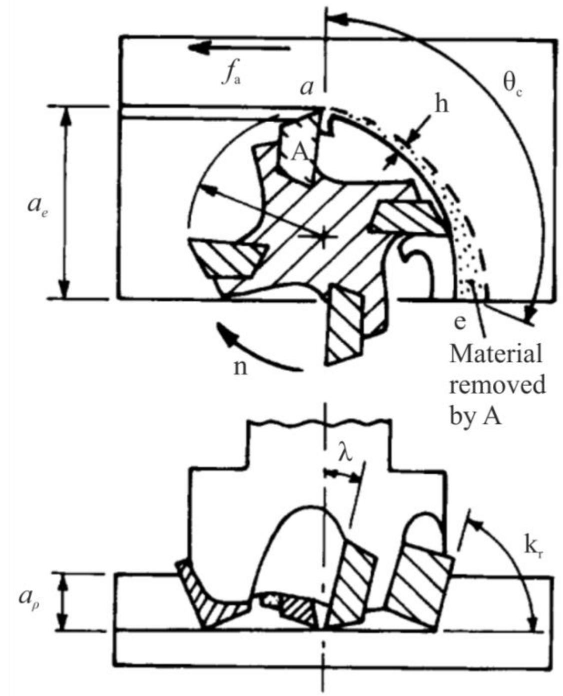
Machining of fiber reinforced materials
General characteristics of milling processes

Characteristics:

- Material removal through the action of cutting teeth under high dynamic
- Cutting tool geometry is selected according to:
  - cutting operation (e.g. trimming, gap milling, surface milling, …)
  - material to be processed
- Operational parameters (e.g. feed f_z, cutting speed $v_{c,}$ cutting width a_e) are selected according to the tool properties and the material to be processed

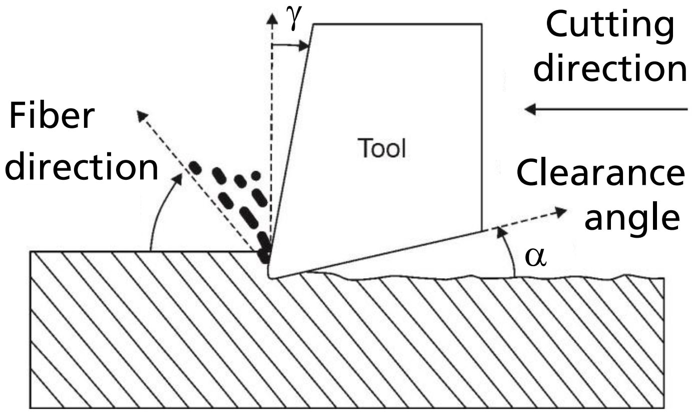
Applications:

- High removal of surface material
- Manufacturing of grooves, slots, etc.
- Material trimming and edge finishing



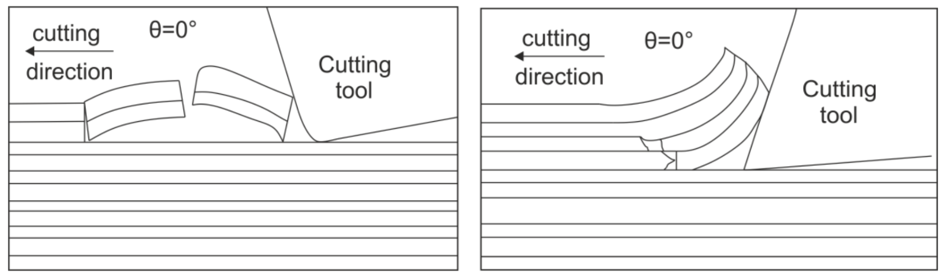
Source: Childs, 2000

Machining of fiber reinforced materials
Influence of the cutting and fiber direction

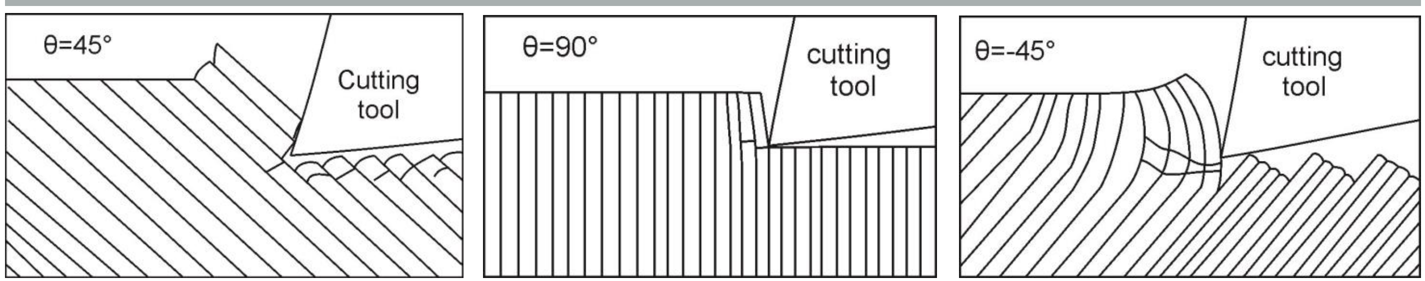


Source: Wang, D., 1995

Influence of the rake angle for fiber direction $\theta = 0°$



Influence of the fiber direction for positive rake angle γ

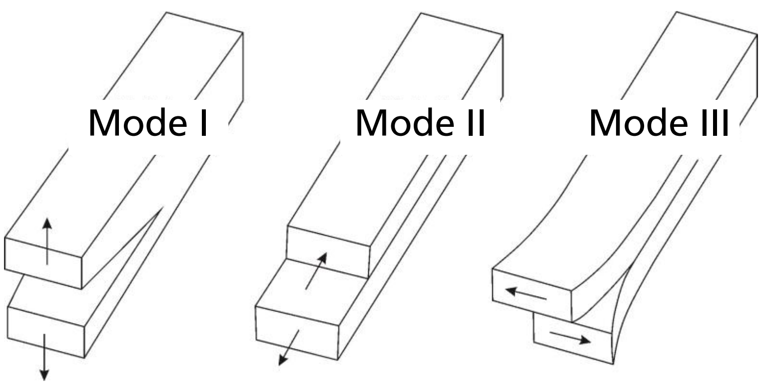


- The cutting direction with respect to the fiber orientation affects chip breakage mechanics and the quality of the processed surface

Machining of fiber reinforced materials
Machining quality

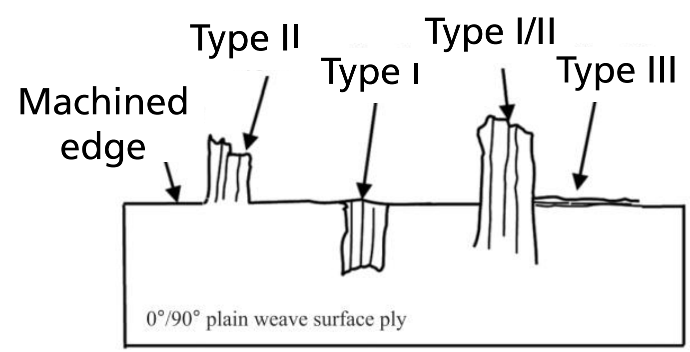
Damage types	Form of appearance
Mechanical damage	Delamination (I,III), fiber linting (I,II), fiber pullout (II) and generation of multiple cracks on the material surface (I)
Thermal damage	Damage (melting or carbonization) of matrix material through overheating (III)
Chemical damage	(Specially under lubrication) Weakening of the bonding at the fiber-matrix interface e.g. through moisture absorption (III).

Delamination modes between plies



Source: Ding W., 1999

Delamination on the surface of a ply



Source: Sheikh-Ahmad J., 2012

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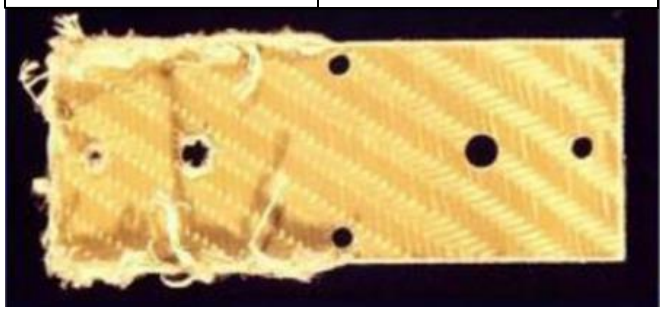
Machining of fiber reinforced materials

Machining quality

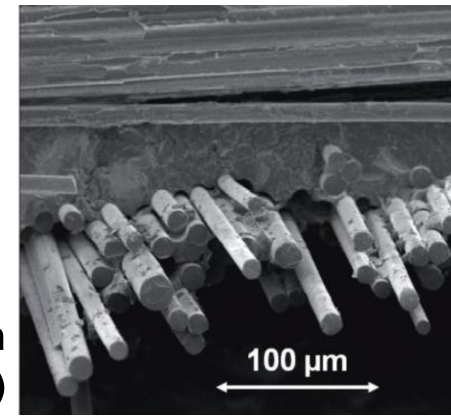
Inadequate tool geometry	*Adequate tool geometry*



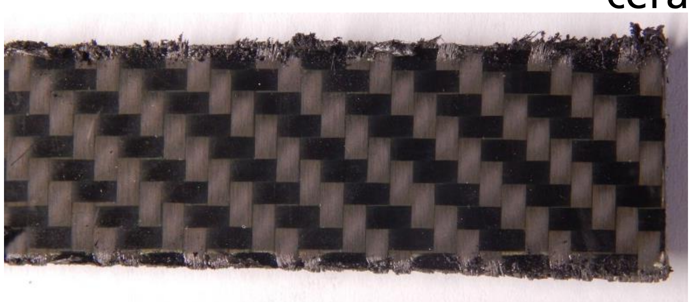
Visible fiber linting (left side) after machining an aramid fiber composite with an inadequate tool geometry

Source: Davim P., 2009

Microscopic image of fiber pullout on surface of a ceramic matrix composite (CMC)



Source: Raether, F., 2013



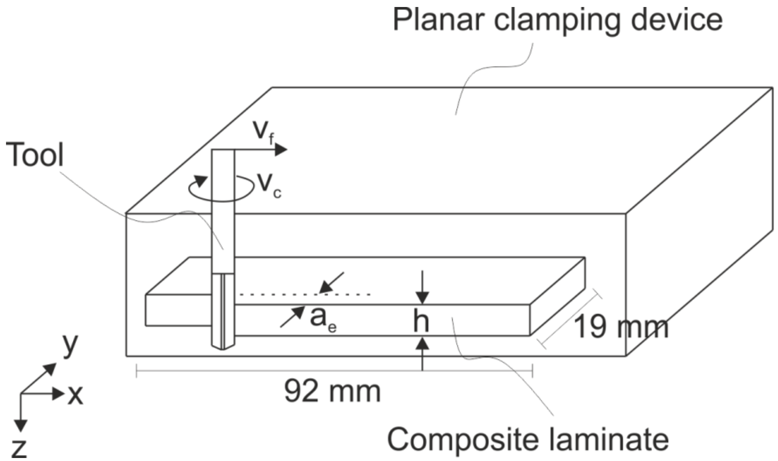
Source: Fraunhofer IPA, 2016

Visible fiber pullout after sawing operation on CFRP laminate with a thermoplastic matrix

Challenge for the simulation technology:
Consideration of anisotropy of composite structures under the process conditions of machining operations

Experimental and simulation setups
Design of experiments and setup - Kinematics

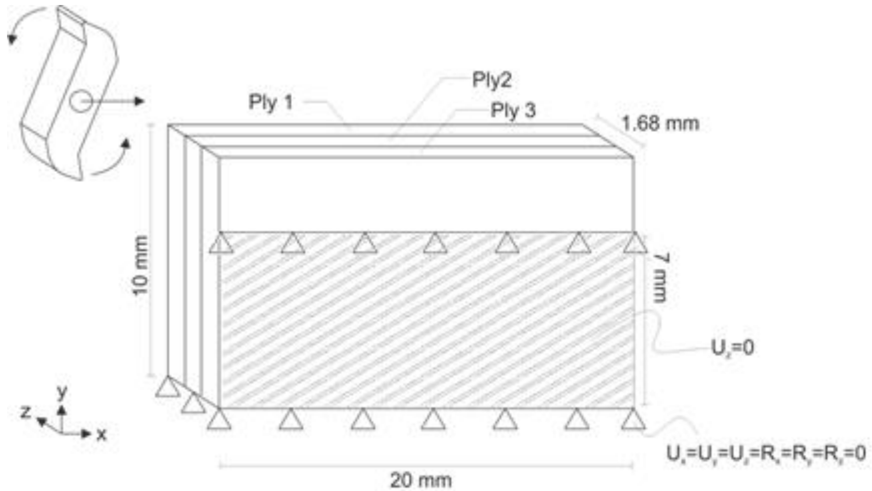
Experiment



Process: Side milling (dry)

*h = 5.04 mm

Simulation



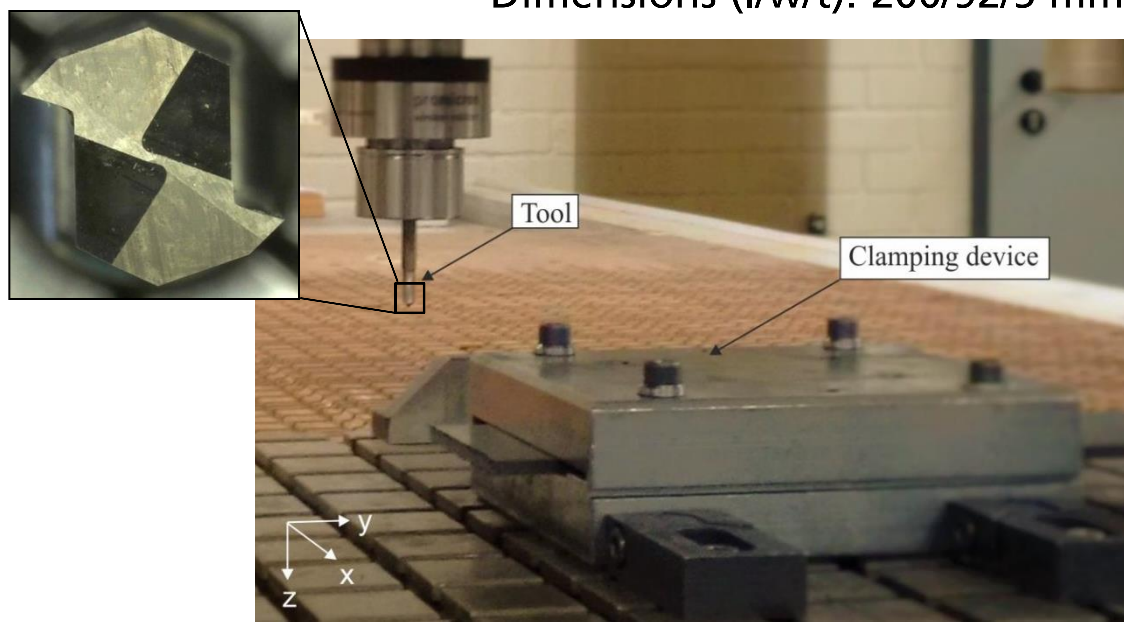
Process: Side milling (dry) with simplification of the workpiece thickness *t = 1.68 mm

Operation parameters: Cutting depth a_e: 2 mm
Feed velocity v_f: 11/14 m/min
Cutting speed v_c: 260 m/min

Experimental and simulation setups
Design of experimental tests

Tool properties
Material: Carbide (EMT 100)
Tool diameter: 6 mm
Cutting edges: 2
Rake/Clearance angles: 10°/20°
Cutting edge radius: 30 µm

Workpiece properties
Material: CFRP
Fiber orientation: $[90°/0°]_{3s}$
Number of plies: 9
Ply thickness: 0.54 mm
Dimensions (l/w/t): 200/92/5 mm



Process: Side milling (dry)

Operation parameters:
Cutting depth a_e: 2 mm
Feed velocity v_f: 11/14 m/min
Cutting speed v_c: 260 m/min

Experimental and simulation setups

Design of the FEM model

Tool properties

Material: Rigid (MAT20)
Number of elements: ~1800
Element size: 0.2 mm
Element type 2: Selective reduce integrated hexa.

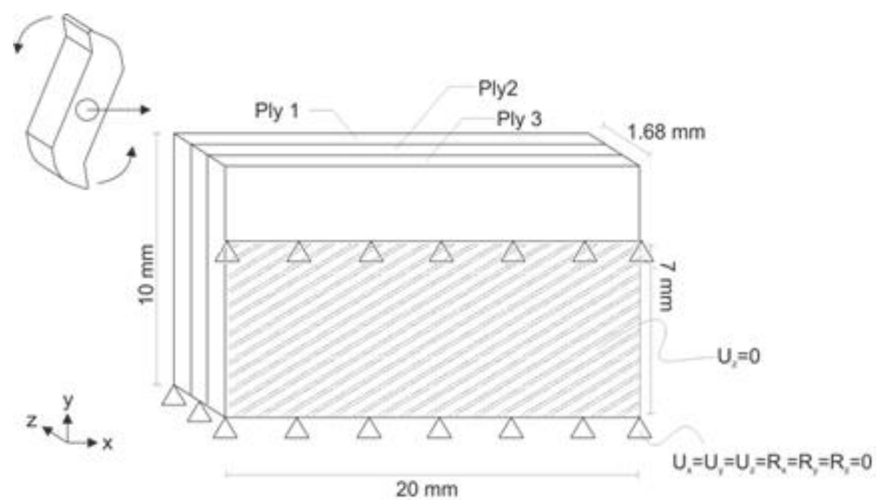
Contact definition

Tool - workpiece:
1) Eroding surface to surface
2) Single surface

Between plies:
3) Automatic one way surface to surface tiebreak

Workpiece properties

Material: Enhanced composite damage (MAT54)
Number of elements: ~15 000
Element size: 0.27 mm
Element type 1: Constant stress hexa.
Dimension [l/w/t]: 20/10/1.68 mm
Number of plies: 3
Fiber orientation: [90°/0°/90°]
Failure criteria: Chang- Chang and mod. Tsai-Wu (MAT54)



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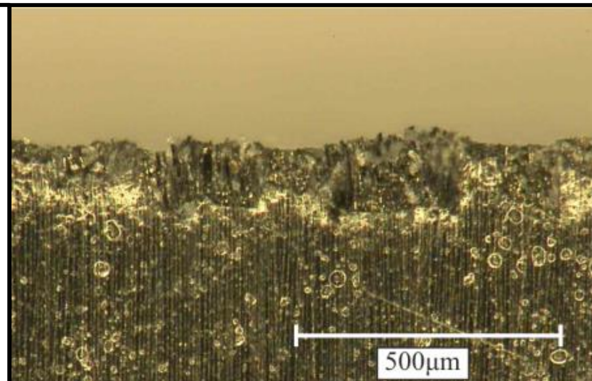
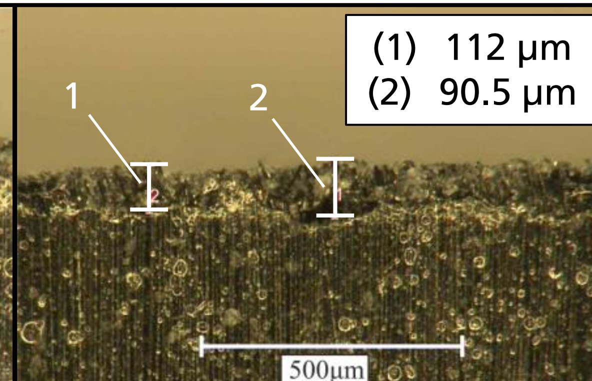
Results and discussion

Delamination on the surface on UD-CFK test samples

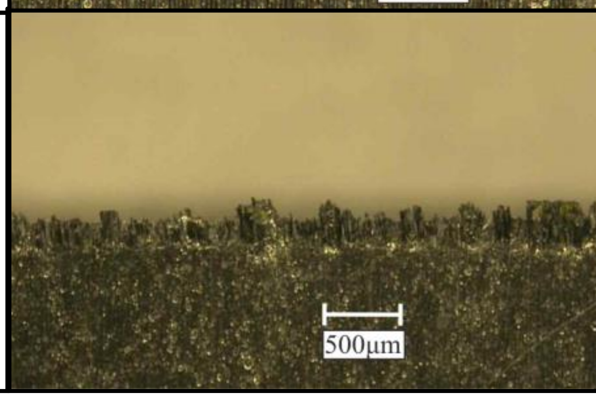
Experimental results

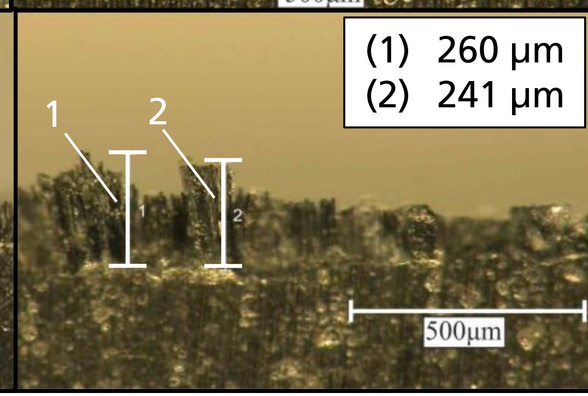
Feed speed
v_f = 11 m/min





Feed speed
v_f = 14 m/min

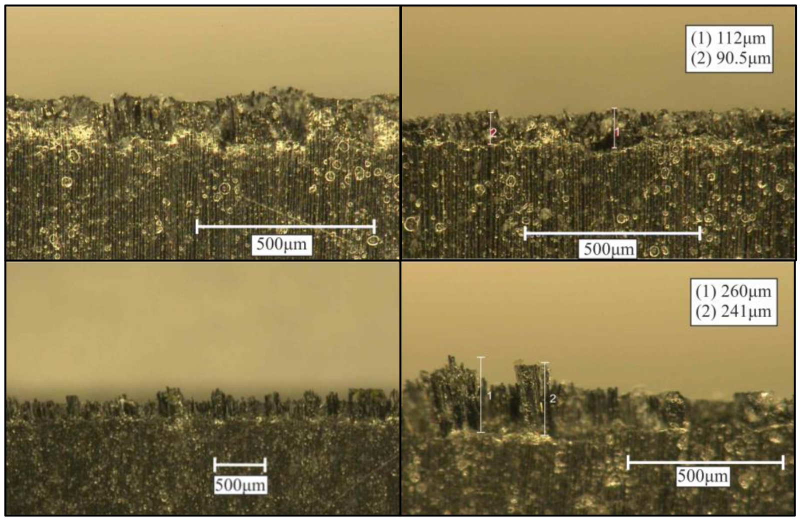




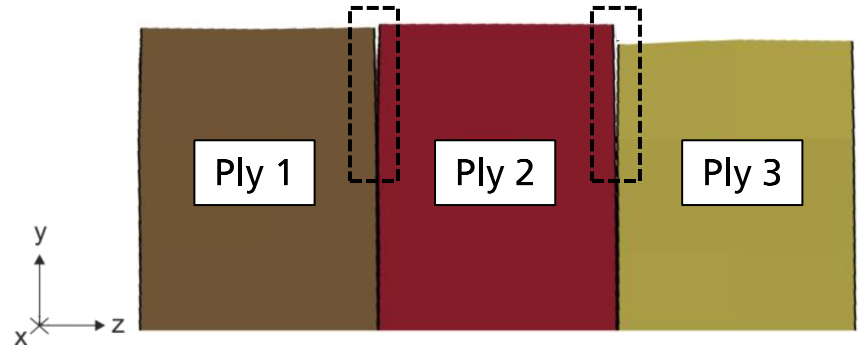
- Delamination on the surface of the test samples increases with the increase of feed speed

Results and discussion
Delamination

Experiment



Simulation



Depth of the delamination between plies		
Feed velocity v_f	11 m/min	14 m/min
Between plies 1 - 2	0.0033 mm	0.021 mm
Between plies 2 - 3	0.011 mm	0.124 mm

Visible surface delamination but no delamination between the plies detected

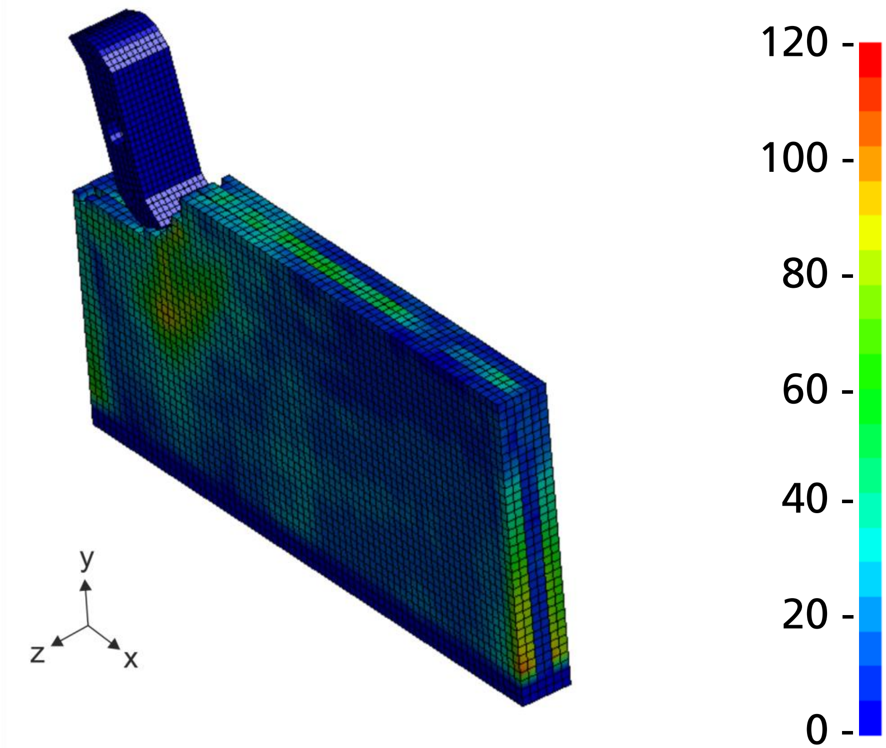
No surface delamination is visible but delamination between plies takes place

- The increase of the feed speed increases the both delamination degrees

Results and discussion

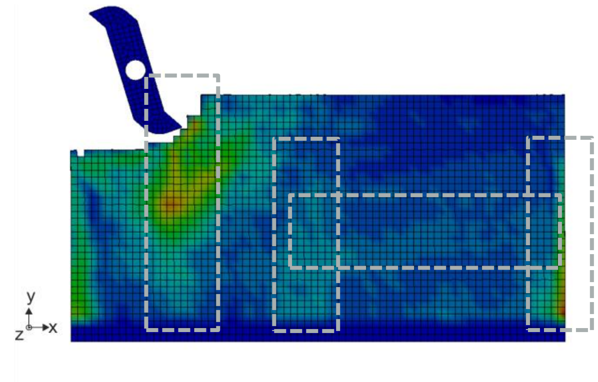
Stress distribution in the simulation of milling UD-CFK

Von Mises Stress [MPa]

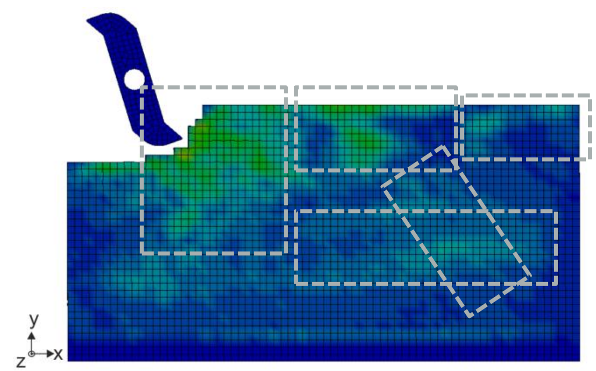


Work piece: 3 Layers of UD-CFRP (90°/0°/90°)

1st und 3rd plies of UD-CFK

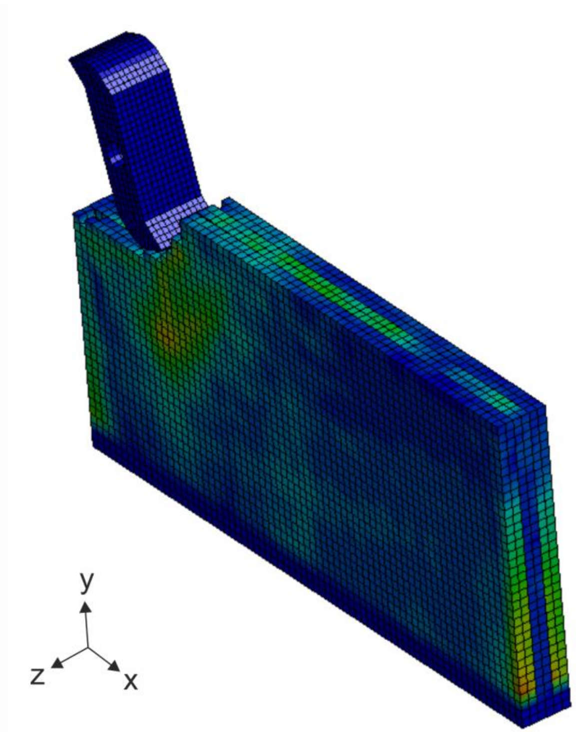


2nd ply of UD-CFK

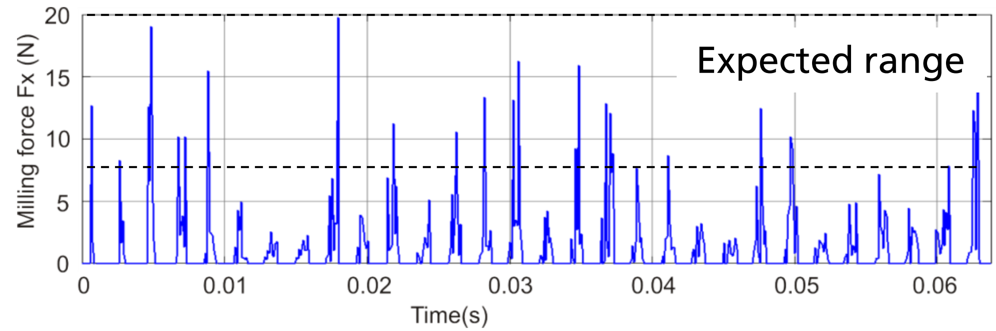


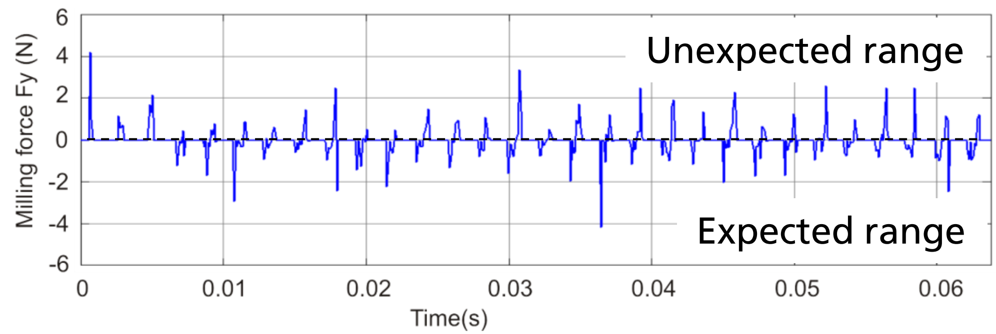
Results and discussion

Cutting forces by the simulation of milling cross-ply CFRP



Work piece: 3 Layers of UD-CFRP (90°/0°/90°)





- Cutting forces in direction of the feed (*x*-direction) fluctuate mostly at a higher magnitude than on the *y*-direction.

Conclusions and outlook
FE-Simulation of delamination when milling CFRP

Conclusions

- A milling process of a cross-ply CFRP laminate has been simulated:
  - The simulation results represent delamination between plies but no delamination on the surface.
  - The simulated model shows a qualitative reasonable response of the stress propagation along the fiber direction and between the contacting plies. However additional experimental tests must be done to verify this.
  - The predicted cutting forces are qualitatively acceptable. However additional experimental tests must be done to verify this.
- The experimental results presented delamination on the surface of the CFRP structures
- Both simulation and experimental results show that an increase on the feed velocity induces an increase on the delamination

Conclusions and outlook
FE-Simulation of delamination when milling CFRP

Outlook

- Alternative models to simulate surface delamination must be conceptually designed and evaluated, e.g. simplified heterogeneous structures.
- The precision of the predicted milling forces with the use of MAT54 will be evaluated with use of experimental measurements of the milling forces.
- An optimization of the contact definition and damage model will take place.
- An experimental quantification of the residual stresses on the CFRP structure due to milling operations should be studied.
- A sensitivity analysis of mesh refinements on the modelling on milling with MAT54 will be carried out.

Thank you for your attention!

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