In-situ Monitoring of Delamination in CFRP Laminates during Drilling

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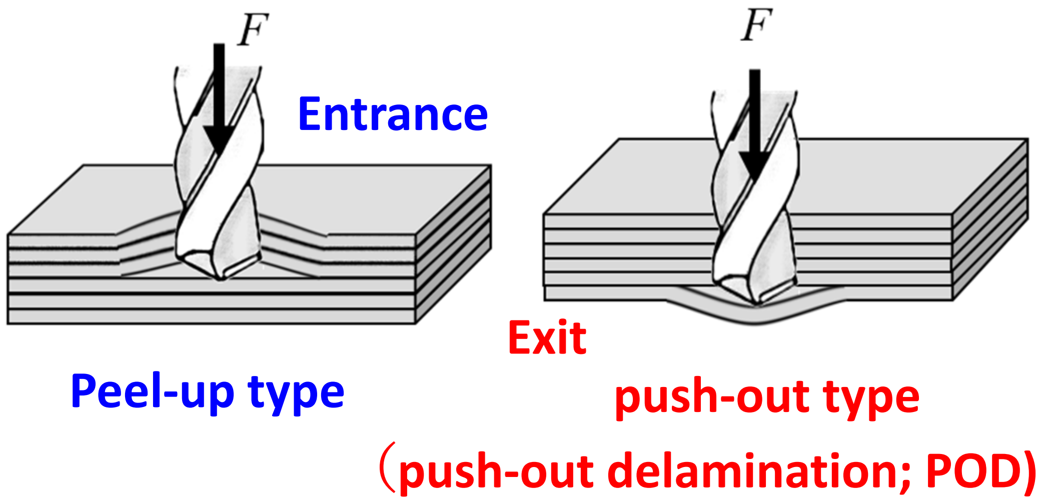
Purpose and background

CFRP（Carbon Fiber Reinforced Plastic） Laminate

Drilling: necessary for mechanical fastening



Issue in drilling

Constraining delamination that leads to strength degradation due to machining

Delamination : detected by non-destructive inspection (NDI) after drilling

Difficult to know (1) strain during drilling, (2) timing of delamination, (3) thrust force for delamination (critical thrust force F_d)

Purpose：measure F_d from the parameters measured during drilling

Flow chart of experiment

Push-in test
Obtain the calibration curve of the thrust force against the strain of the back-up board (thrust strain)

Drilling test
Measure the (1) thrust strain, (2) internal strain (using an FBG sensor), and (3) **electrical impedance** (magnitude and phase angle) to determine the timing of POD and the corresponding thrust strain

Estimation the critical thrust force from the calibration curve obtained from the push-in tests and the thrust strain from drilling tests

In-situ strain and damage monitoring

electrical impedance (magnitude and phase angle) → **Measured by connecting an LCR meter (frequency 1 kHz) to the electrode (conductive paste) around the drilled hole**

Electrical impedance in the thickness direction has a resistance component R and a capacitance component C

→ **High possibility of detecting the timing of delamination during drilling**

Internal strain **(1) FBG sensor embedded in the specimen**
(2) Temperature using TC bonded to CFRP front and back surfaces

Conversion formula

$$\varepsilon\ (\mu\varepsilon) = \frac{1\times 10^{6}}{F_G}\frac{\Delta\lambda}{\lambda_0} - \left(\frac{C_1}{F_G} - C_2\right)\Delta T$$

$\Delta\lambda$: Bragg wave length shift

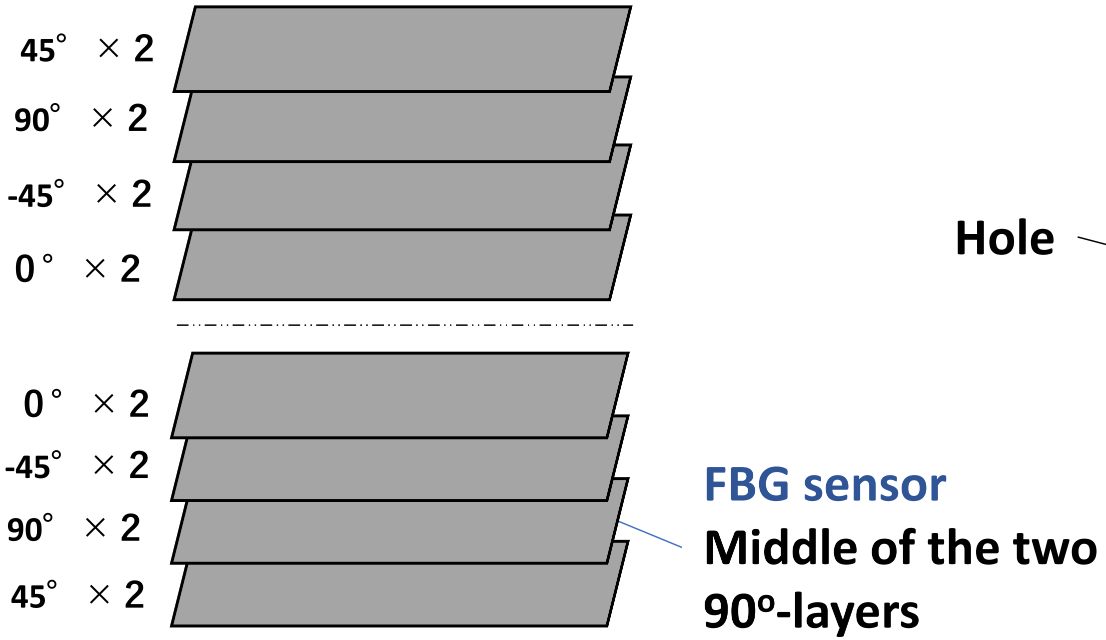
F_G[-]	C_1[μm/m/K]	C_2[μm/m/K]	λ_0[nm]
0.838	6.156	0.7	1550

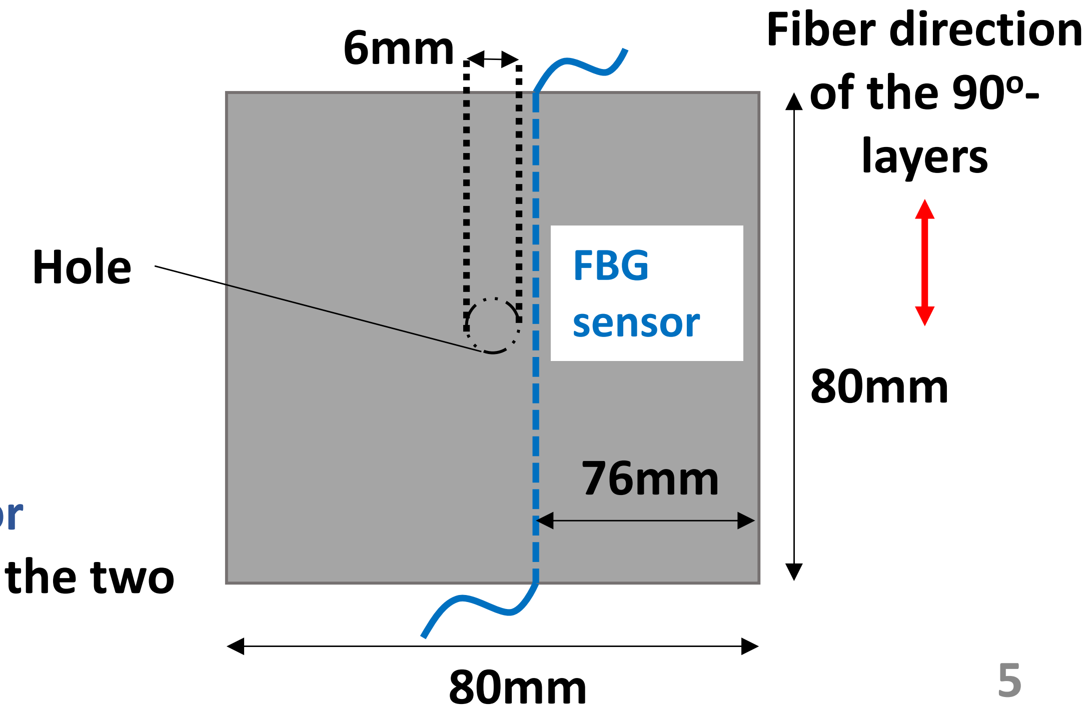
Specimens

Prepreg	Length	Width	Thickness	Stacking sequence
CF/Epoxy (T700S/2592 Vf=0.6)	80 mm	80 mm	2 mm	16-ply QI laminate $[45^{\circ}_2/90^{\circ}_2/-45^{\circ}_2/0^{\circ}_2]_s$

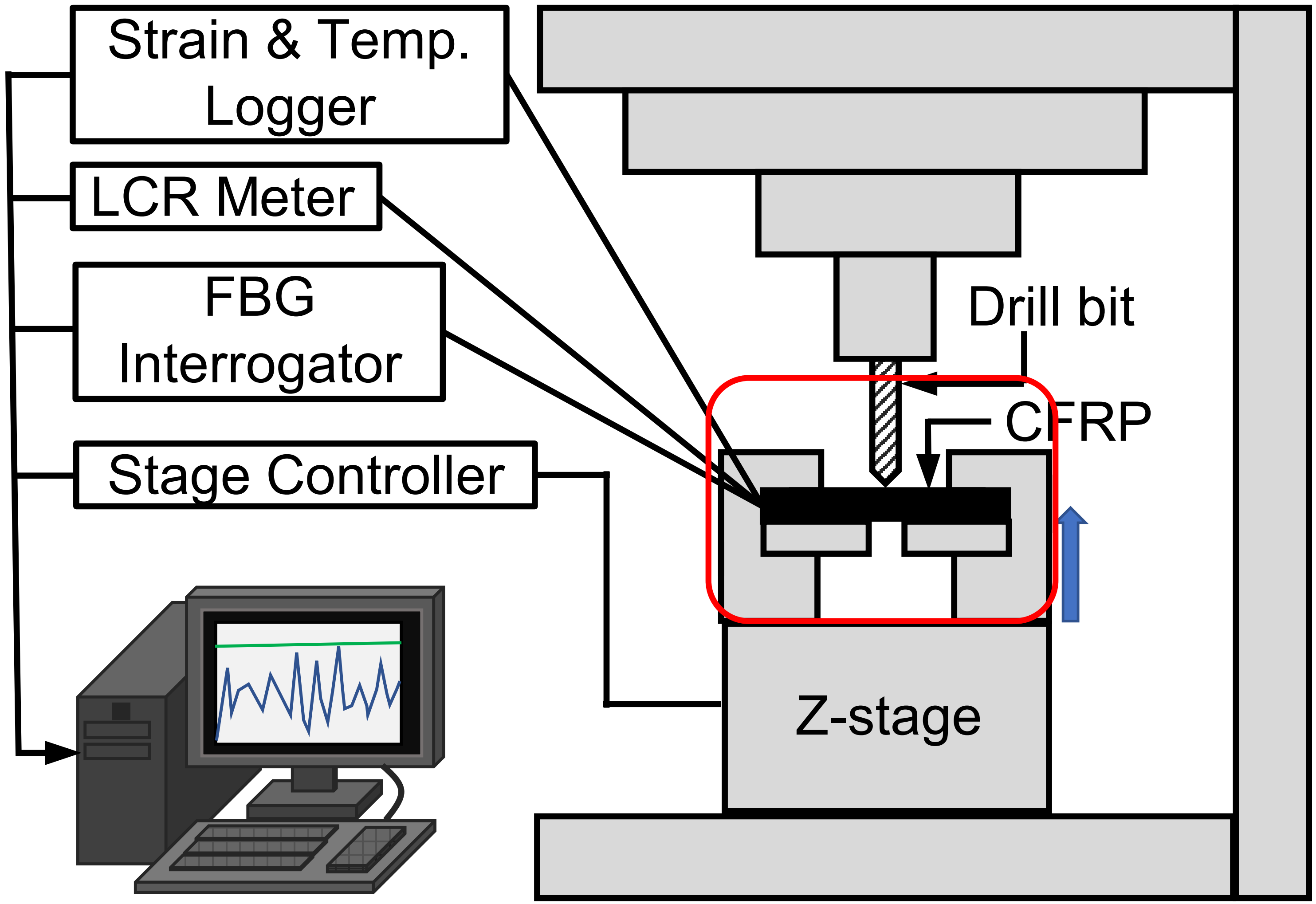
Cure condition using an autoclave
Temp: 130°C for 2 hr under vacuum
Pressure: 0.3 MPa

Resistivity
Fiber : 5.9×10^{-5} Ω・m
Transverse : 7.9×10^{-2} Ω・m
Thickness : 1.0×10^{-1} Ω・m



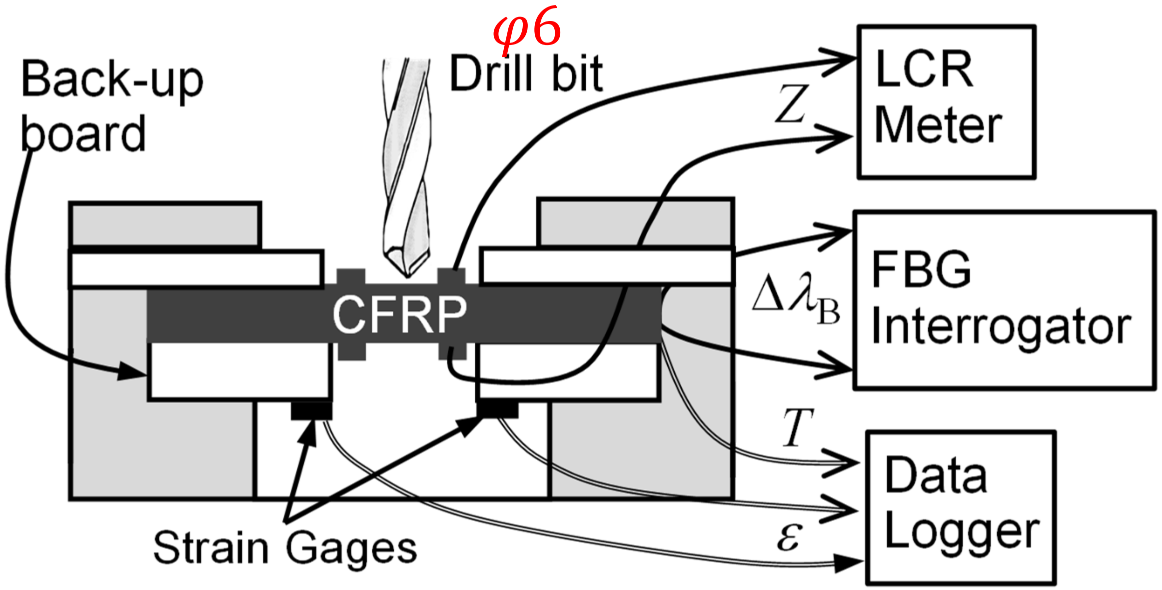


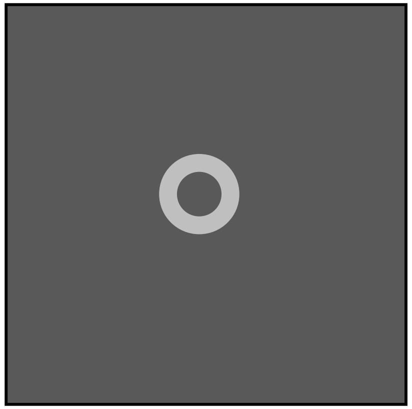
Experimental setup for in-situ monitoring



Drilling test

<u>**Detail of CFRP work**</u>





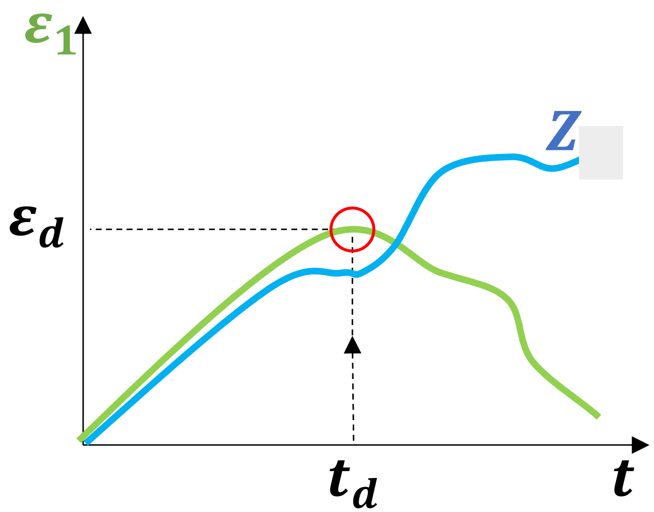
Outer d = 15 mm
Inner d = 6 mm

Ring-shaped electrodes

1. Investigate the thrust strain and impedance vs. time diagrams

2. Determine the timing of POD t_d

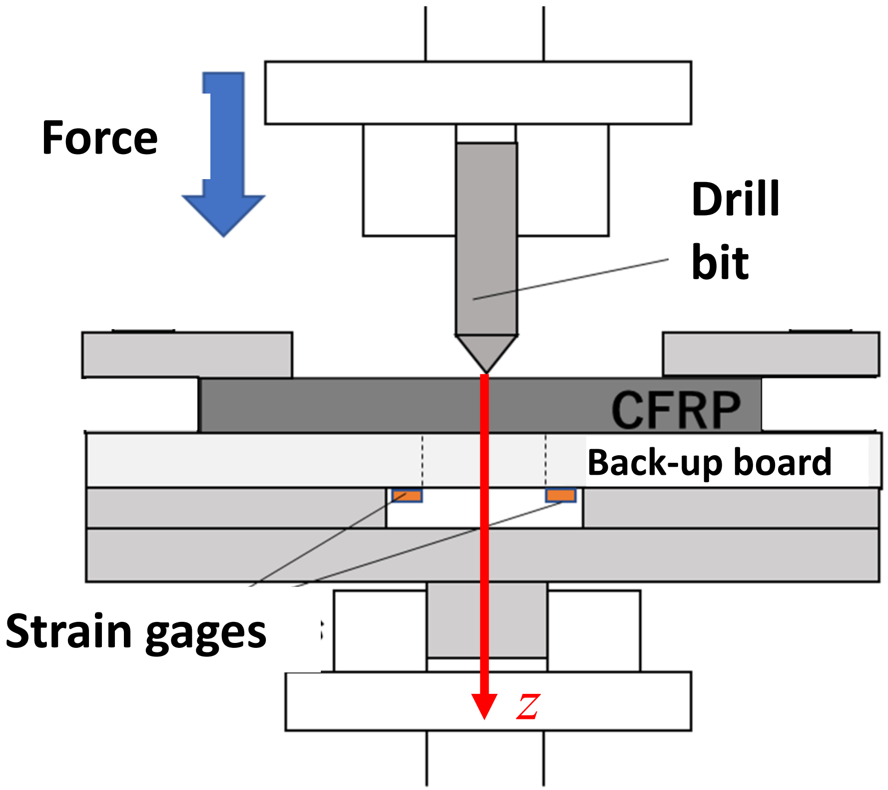
3. Estimate the thrust strain at the timing of POD ε_d

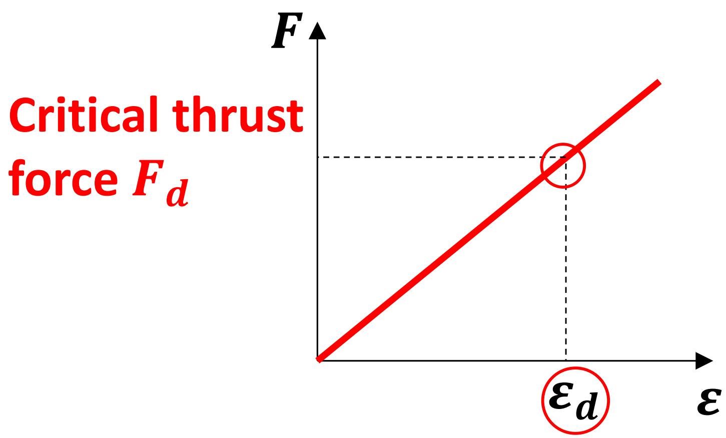


Push-in test

1. For several drilling displacements *z*, a universal testing machine was used to measure the relationship between thrust strain ε and thrust force F by pressing the same drill bit as the drilling test into a pre-drilled hole
2. Create a calibration curve averaging the results for several drilling displacements *z*

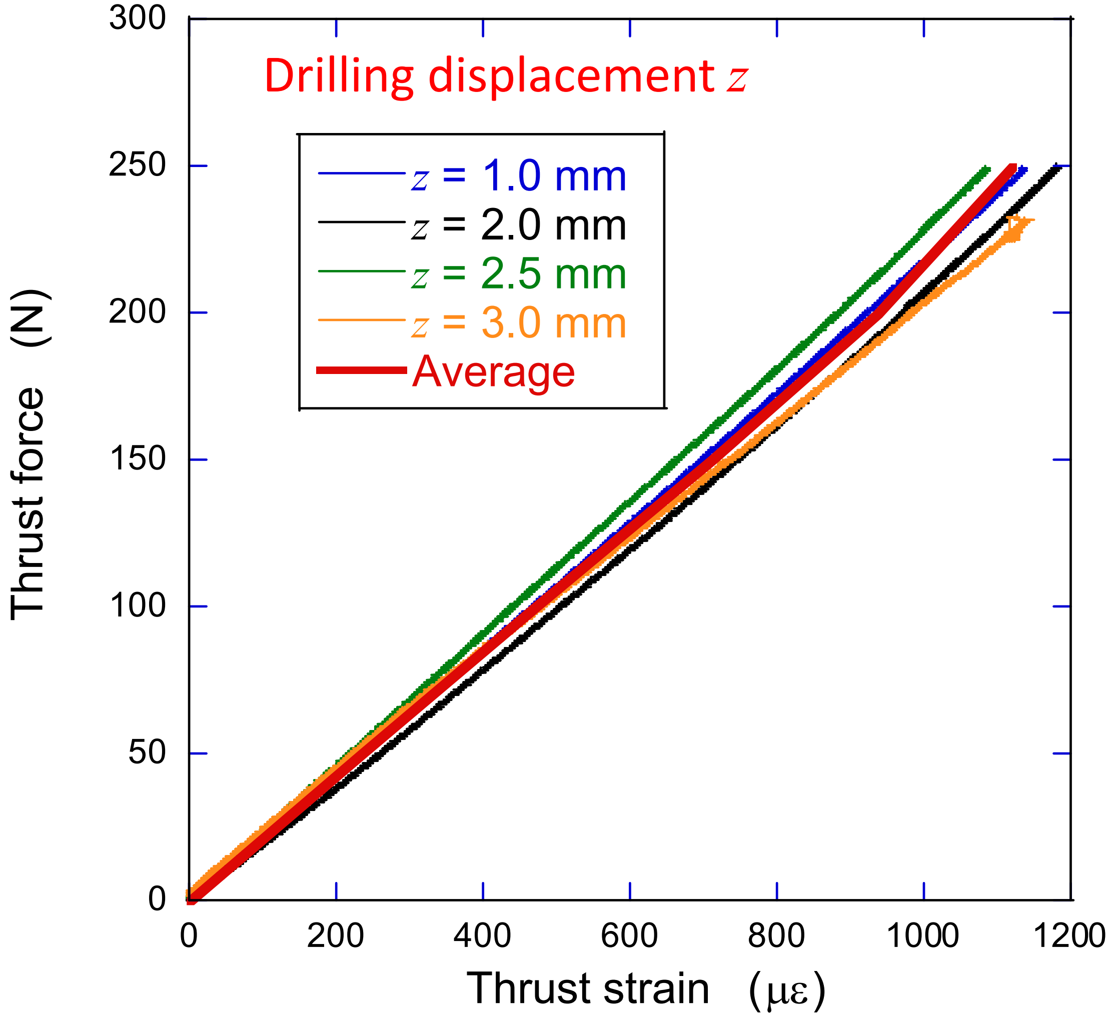
Estimate the critical thrust force from the results of drilling and push-in tests





Calibration curve

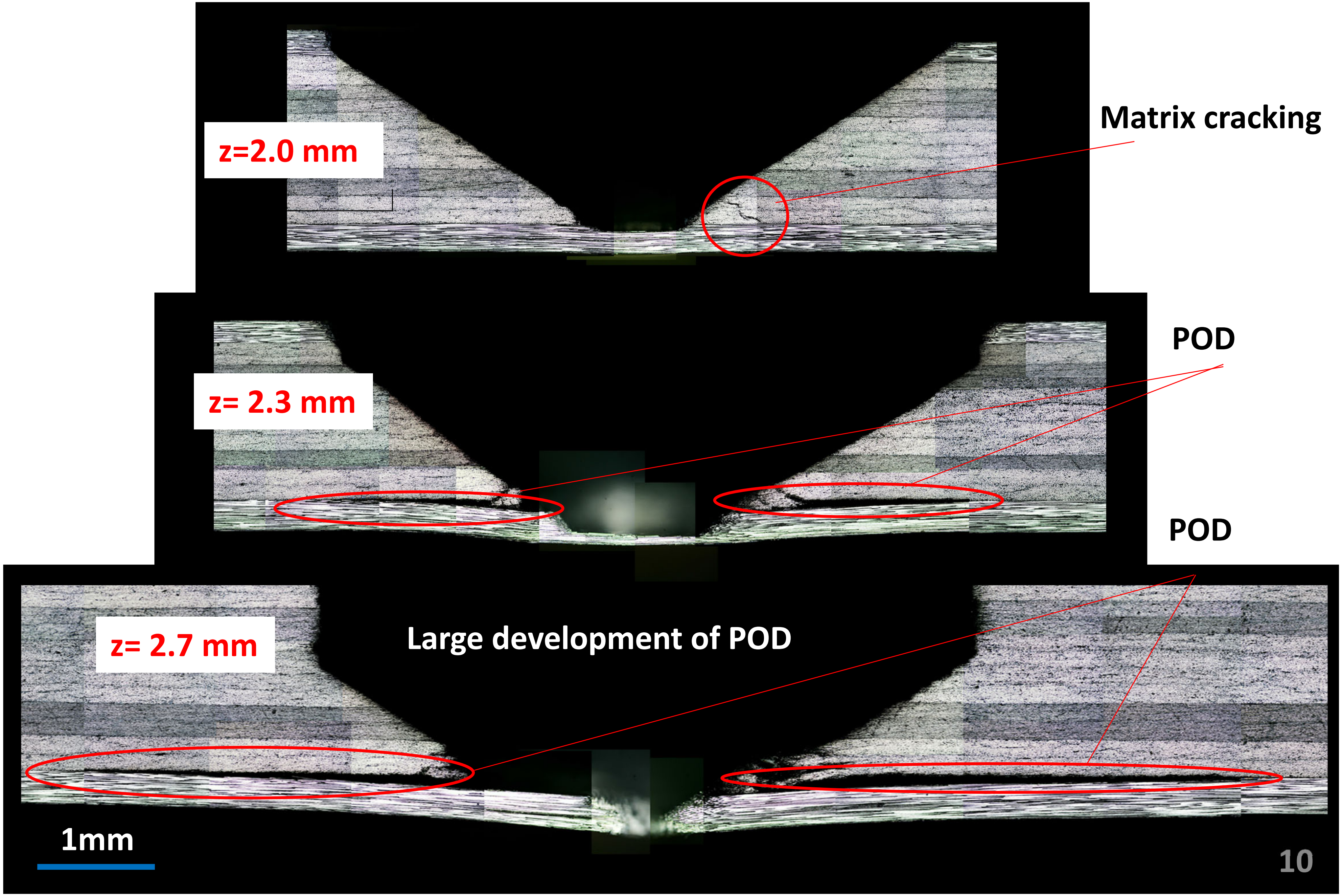
Results of push-in test



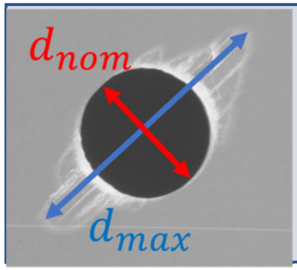
Thrust load-strain diagram is independent of drilling displacement

Calibration curve (red): average of results for each drilling displacement

Cross-section after drilling (1) large POD

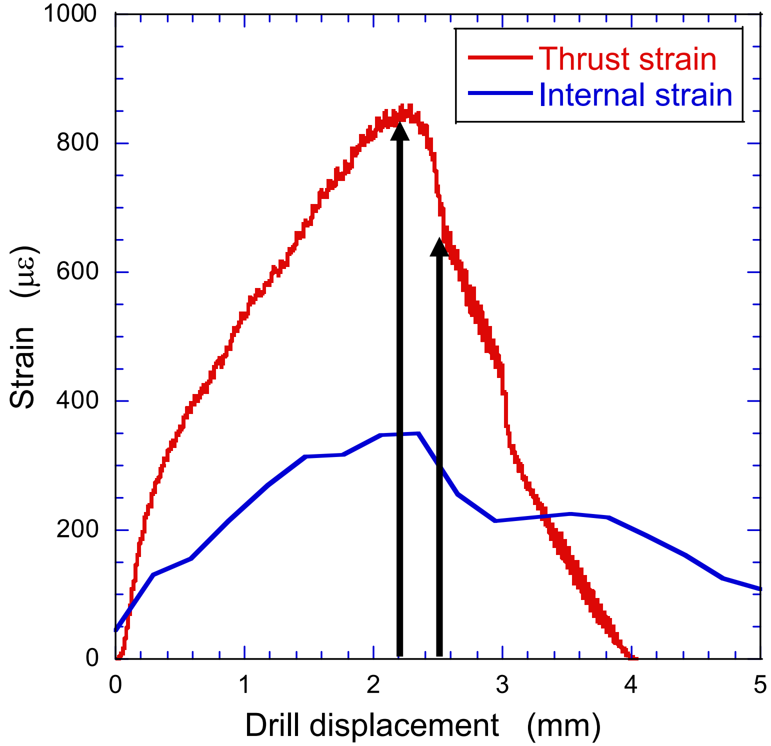


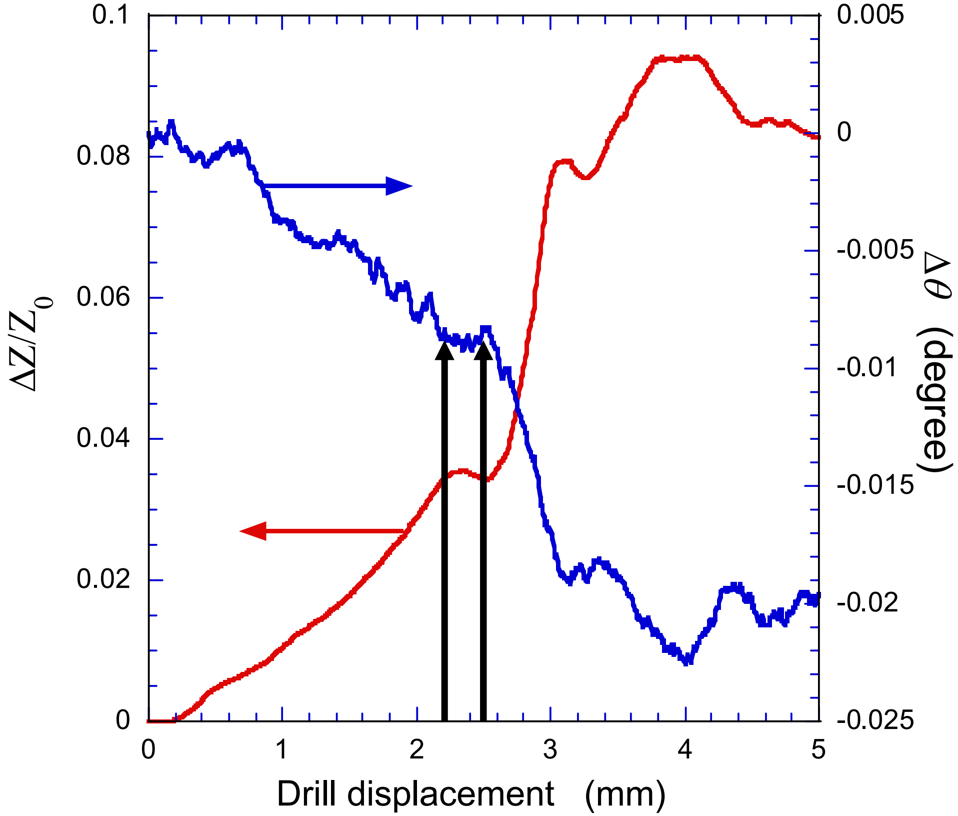
Impedance and strains (1) large POD



$$D_f = \frac{d_{max}}{d_{nom}} = 2.16$$

Rotation speed	Feed rate
540 [rpm]	0.6 [mm/s]





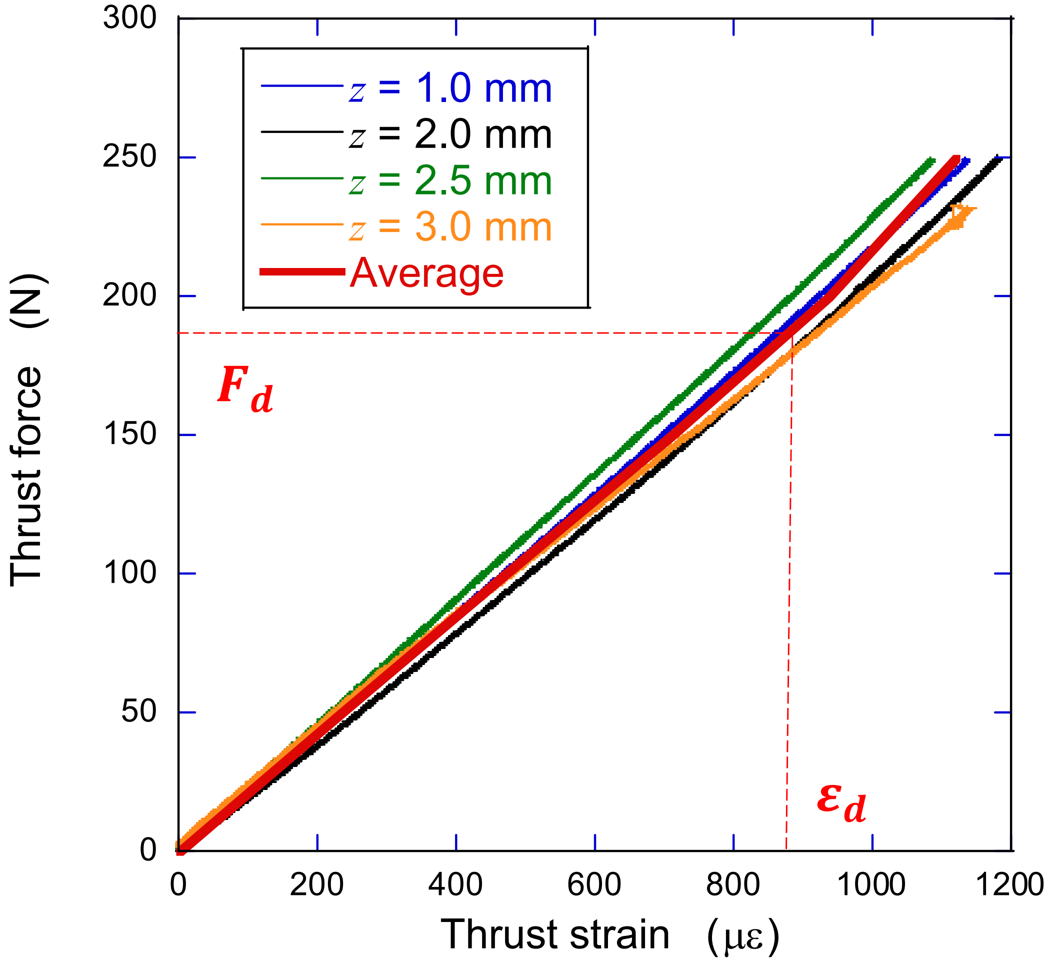
2.2 mm
- **Maximum thrust strain**
- $|\Delta Z|/|Z|$ **is plateau**
- $\Delta\theta$ **is plateau**

→ Initiation of POD

2.5mm
- **Further reduce in thrust strain**
- **Sudden increase in** $|\Delta Z|/|Z|$
- **Sudden decrease in** $\Delta\theta$

→ Propagation of POD

Estimation of critical thrust force

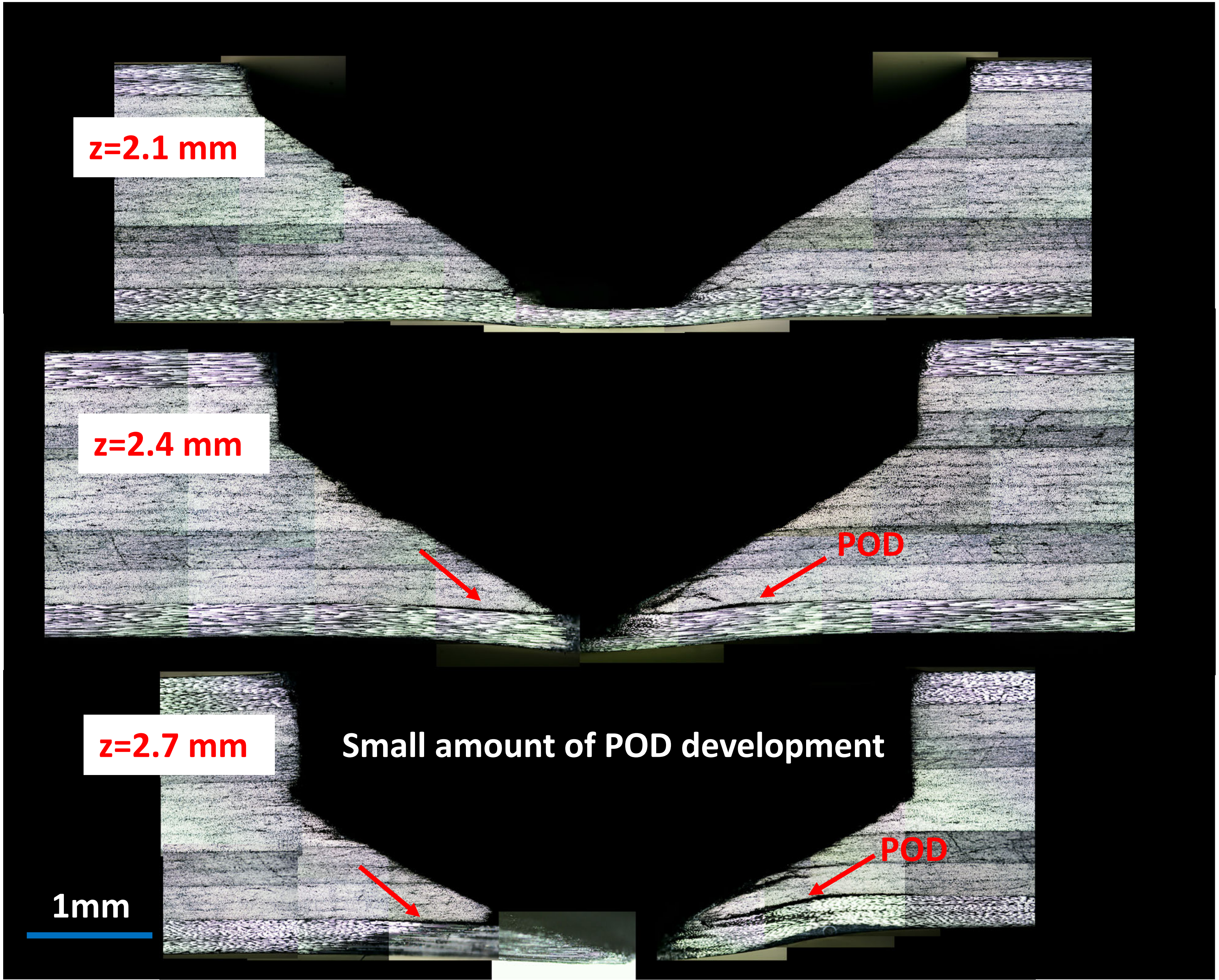


Drilling displacement for POD: y = 2.2 mm

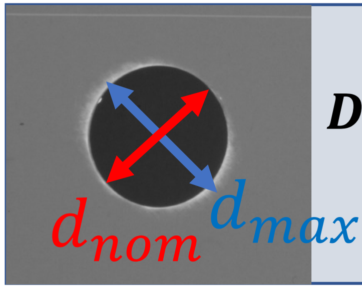
Thrust strain for POD: $\varepsilon_d = 860\ \mu\varepsilon$

Critical thrust force for POD: $F_d = 183$ N

Cross-section after drilling (2) small POD

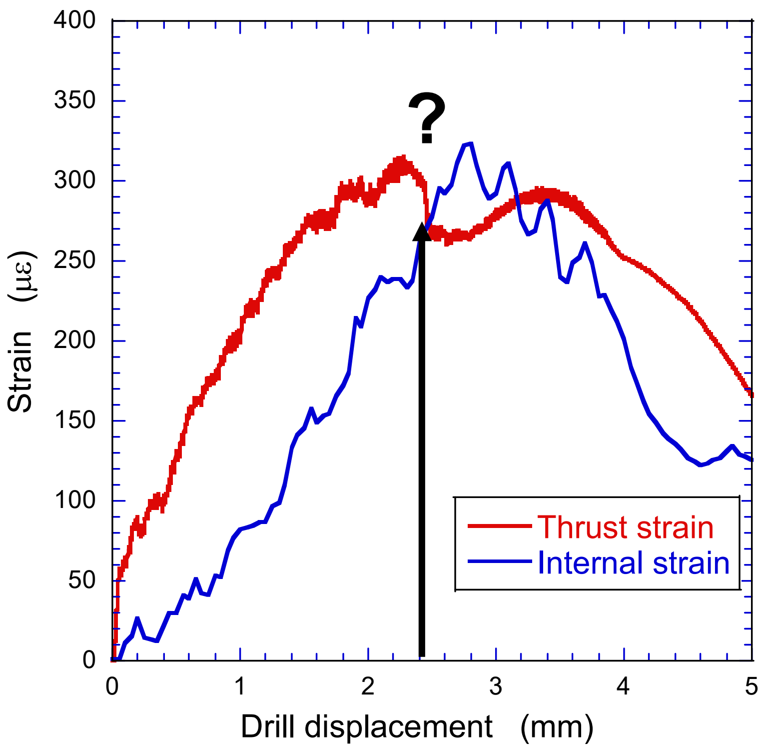


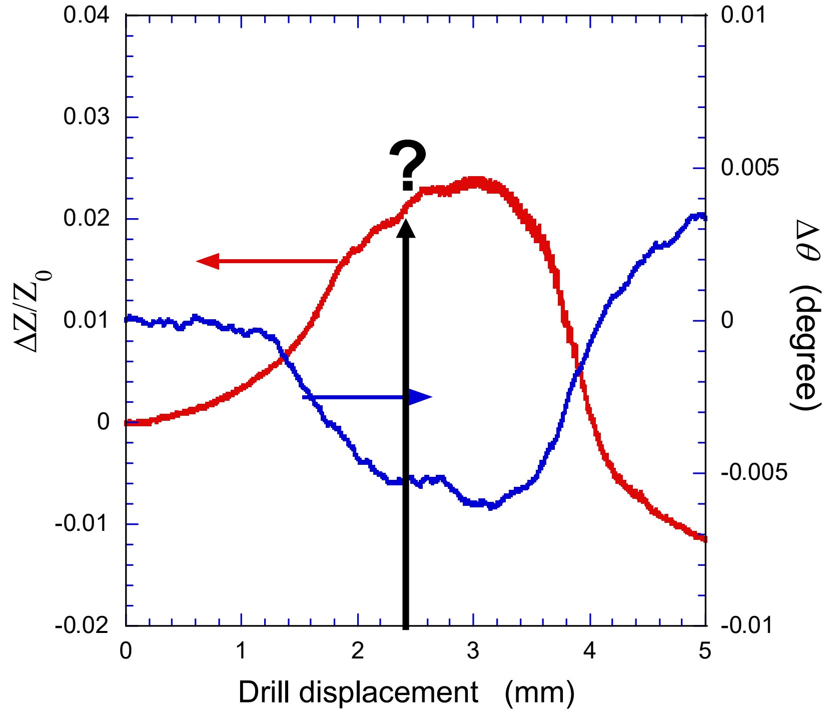
Impedance and strains (2) small POD

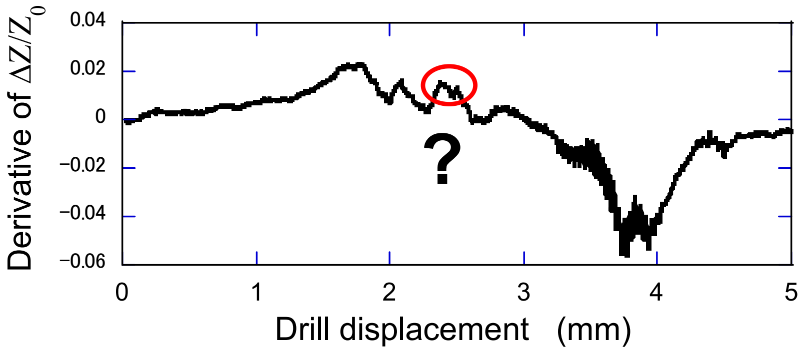


$$D_f = \frac{d_{max}}{d_{nom}} = 1.16$$

Rotation speed	Feed rate
2610 [rpm]	0.1 [mm/s]

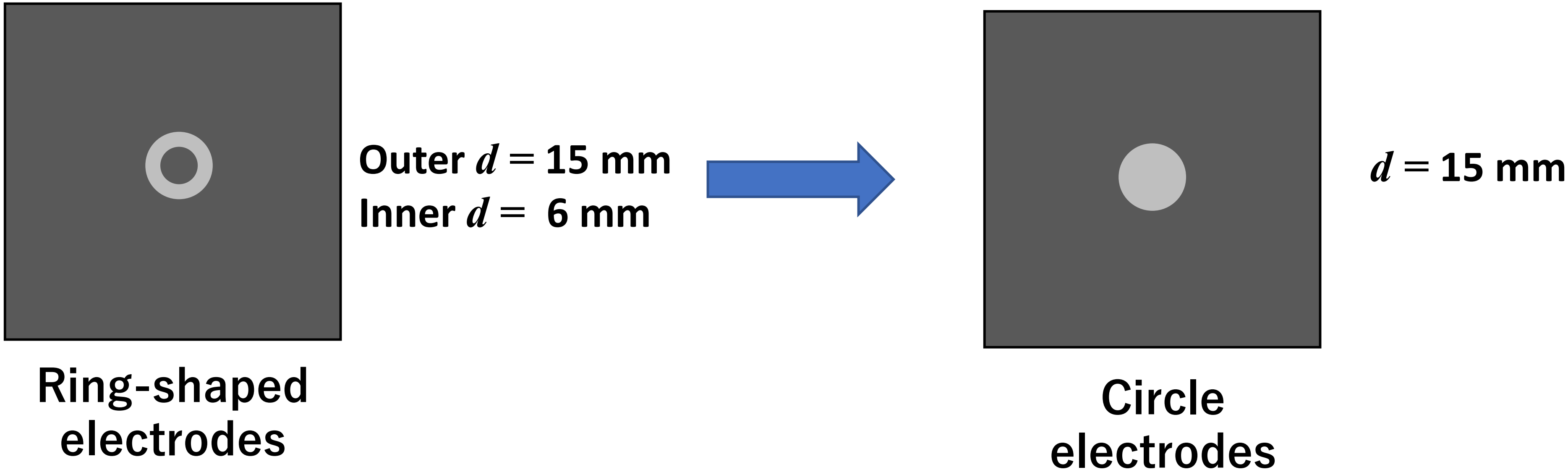






Small changes in the signals
→Unclear signs (small changes) showing delamination onset

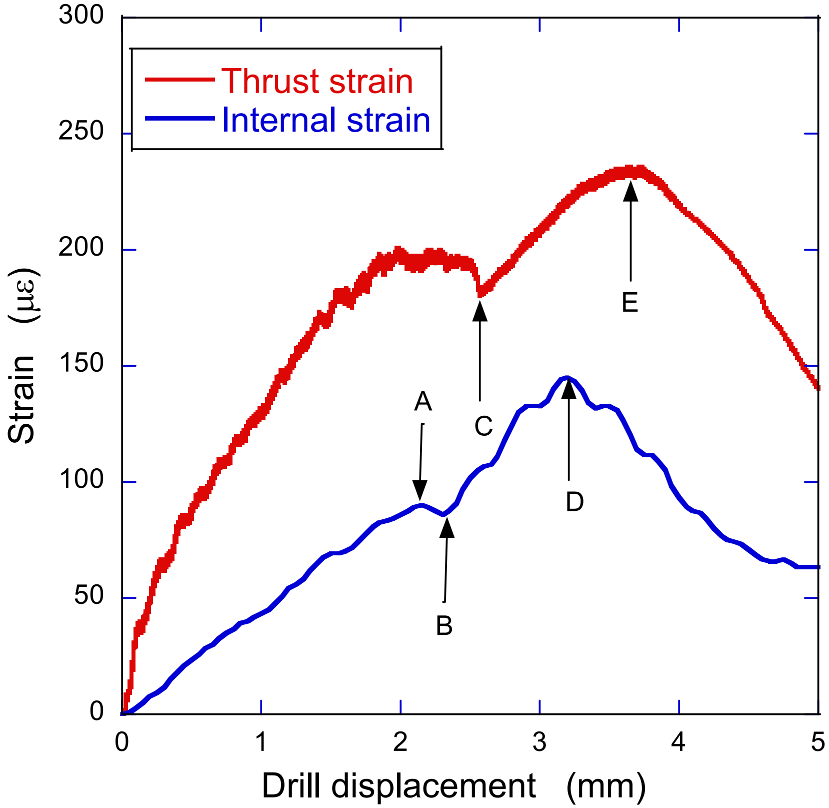
Improvement of electrodes

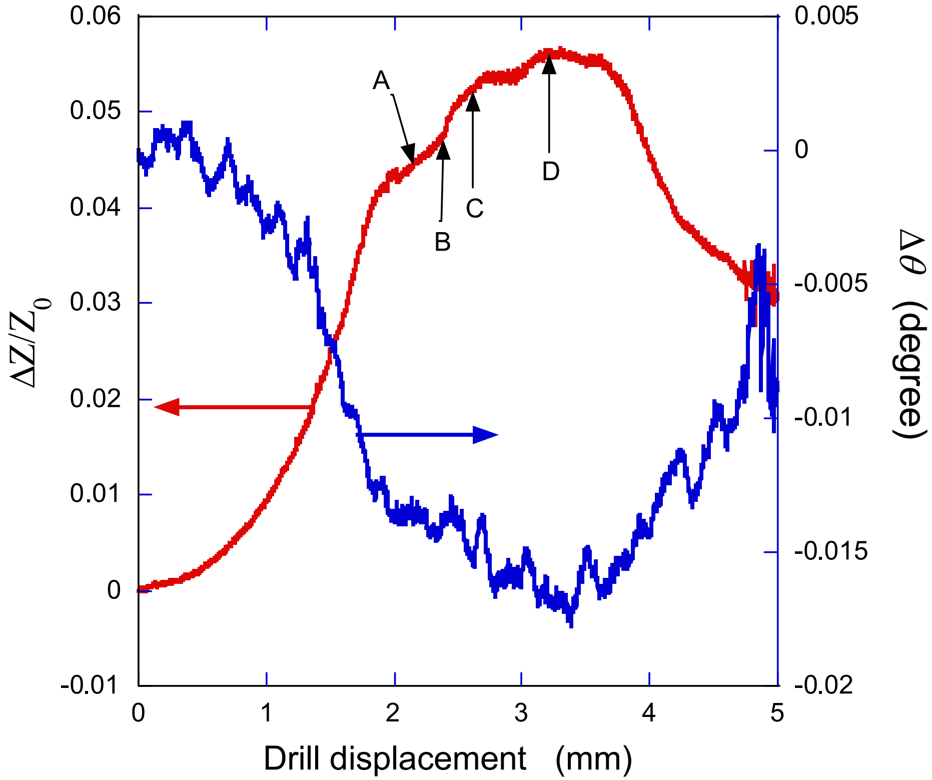


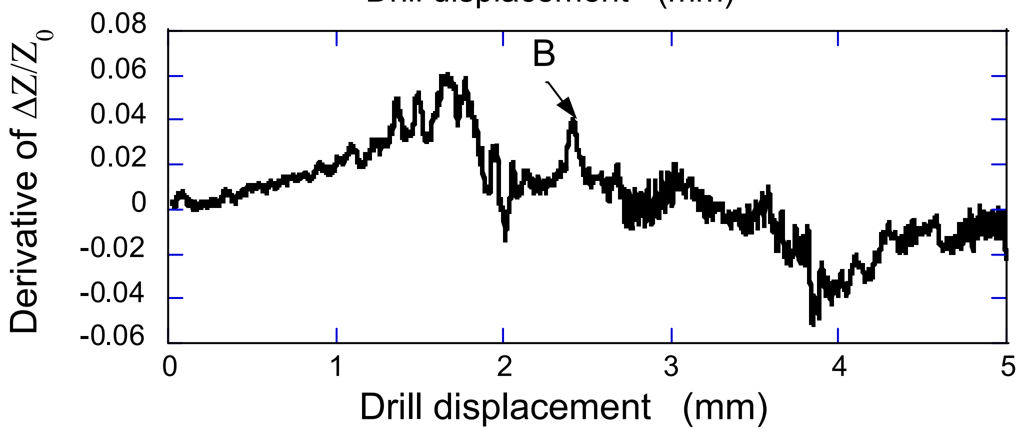
Circular electrodes are used to capture POD smaller than the diameter of the drilled hole

Impedance and strains (2) small POD

A: Plateau starting point, B: Onset of POD
C: End of POD extension, D: penetration of drill tip
E: full penetration of drill lead part (ϕ6)







Thrust strain for POD:

Critical thrust force : $F_d = 42\ \mathrm{N}$

Conclusions

1. The thrust force for POD onset in CFRP drilling was estimated from impedance changes.

2. Onset and propagation of large POD can be clearly detected by the electrical impedance method, whereas for small POD, the impedance change is relatively less clear.

3. POD detection sensitivity is improved by changing from ring-shaped electrodes to circular electrodes.

4. Since POD does not always occur at the maximum thrust force, POD onset cannot be detected from the thrust force alone.