8DAB005856

Tomasz Nowak

Zastosowanie zautomatyzowanych badań ultradźwiękowych w testowaniu elementów izolacyjnych WN wykonanych z kompozytów wzmacnianych włóknami

2025-01-22

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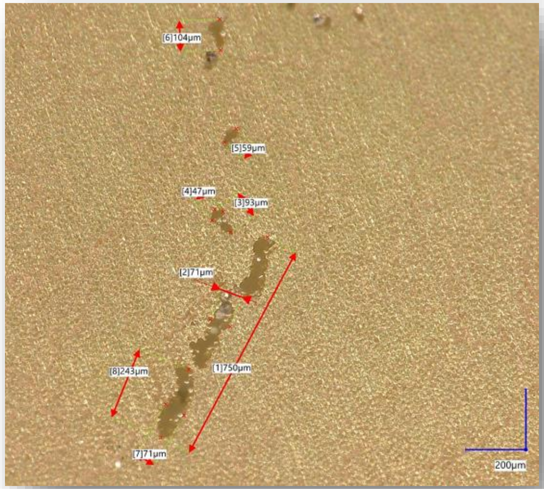
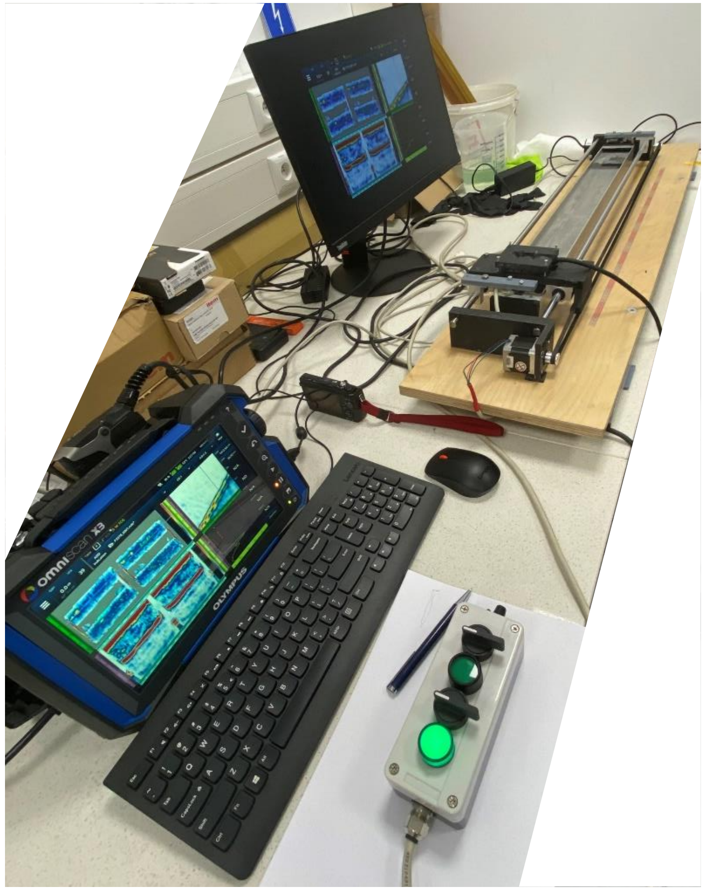
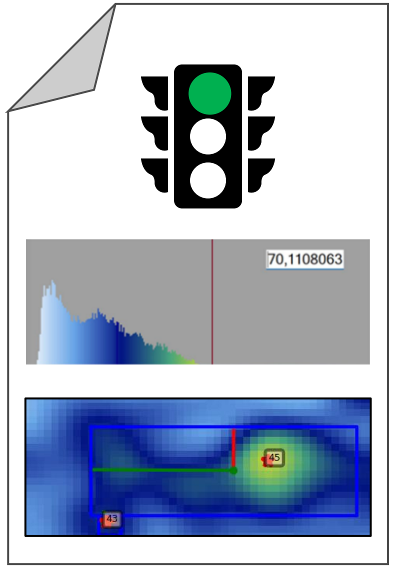
Zakres prezentacji

Zastosowanie zautomatyzowanych badań ultradźwiękowych w testowaniu elementów izolacyjnych WN wykonanych z kompozytów wzmacnianych włóknami







Agenda

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- Izolacja stała WN
  - aplikacje, charakterystyka (zalety / wady)
- Kompozyty włókniste
  - własności, aplikacje, produkcja, wady, metody badawcze NDT
- Technika ultradźwiękowa
  - zasada działania, podstawowe techniki, skany
- Beamforming
  - metody formowania wiązki (PA / TFM), przykłady
- Aplikacja praktyczna
  - produkt, stanowisko, automatyka, software,
- Wyniki
  - porównania, wnioski, co dalej

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1. Izolacja stała

Dlaczego izolacja stała?

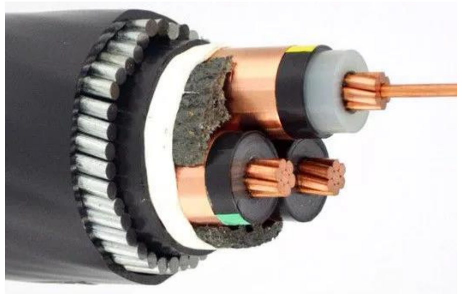
- zapewnia bezpieczeństwo obsługi
- chroni urządzenie

- jest „stała” więc „nie ucieka” (jak olej, czy gazy) – nie wymaga serwisu
- jest „sucha” – bezpieczna dla użytkownika / środowiska
- oferuje dużą stabilność własności w okresie użytkowania

- **pełni funkcję strukturalną – przenosi siły mechaniczne i często stanowi sztywną obudowę**
- **pozwala na stosowanie materiałów gradientowych**
- ...




Izolacja stała - przykłady



Materiały kompozytowe w izolacji WN

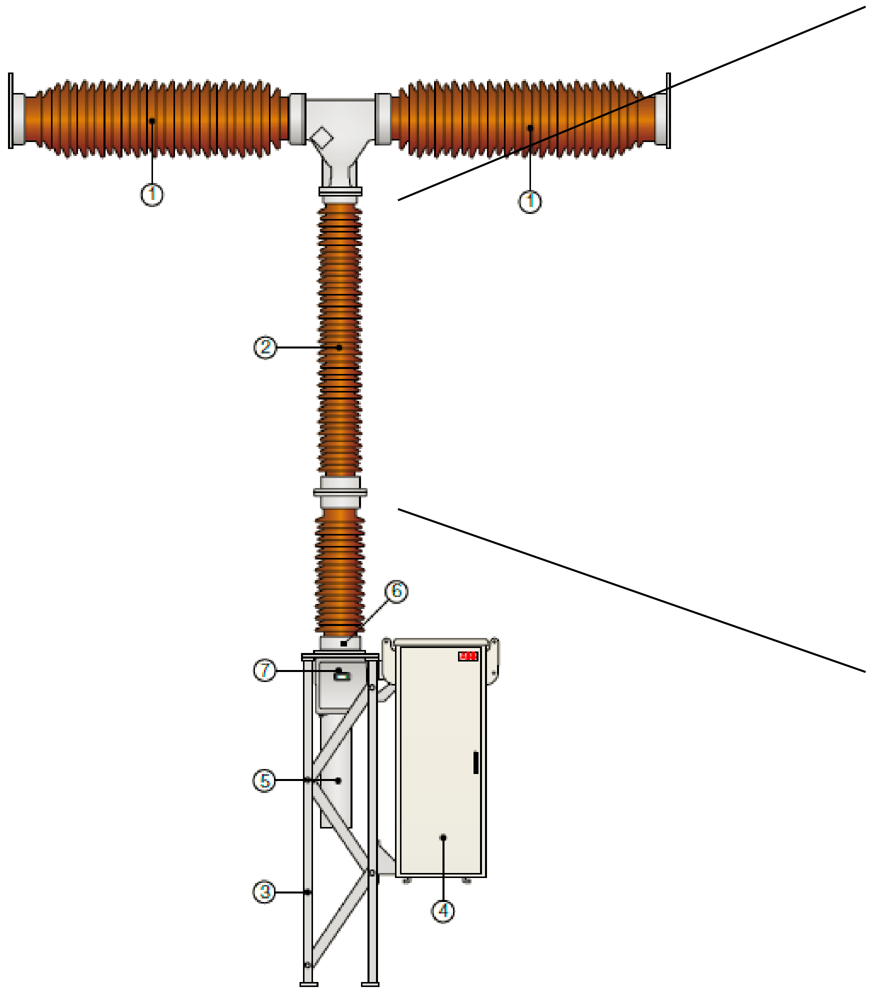
Transformer Bushings

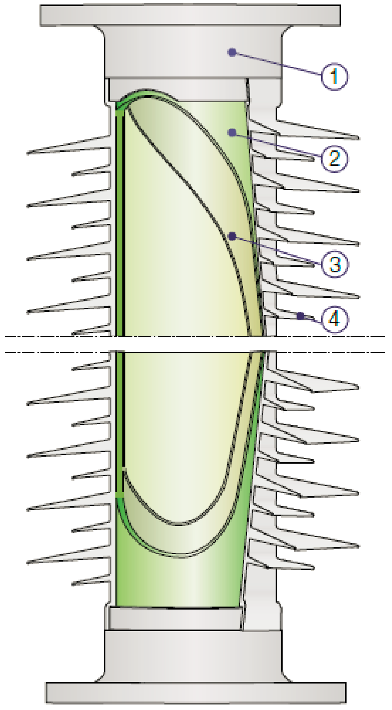
Pole Insulators

HV Circuit Breakers

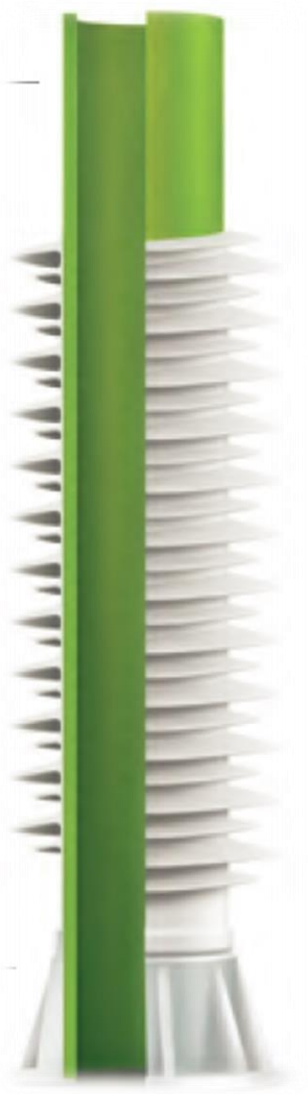
GIS instalations

Izolatory wsporcze

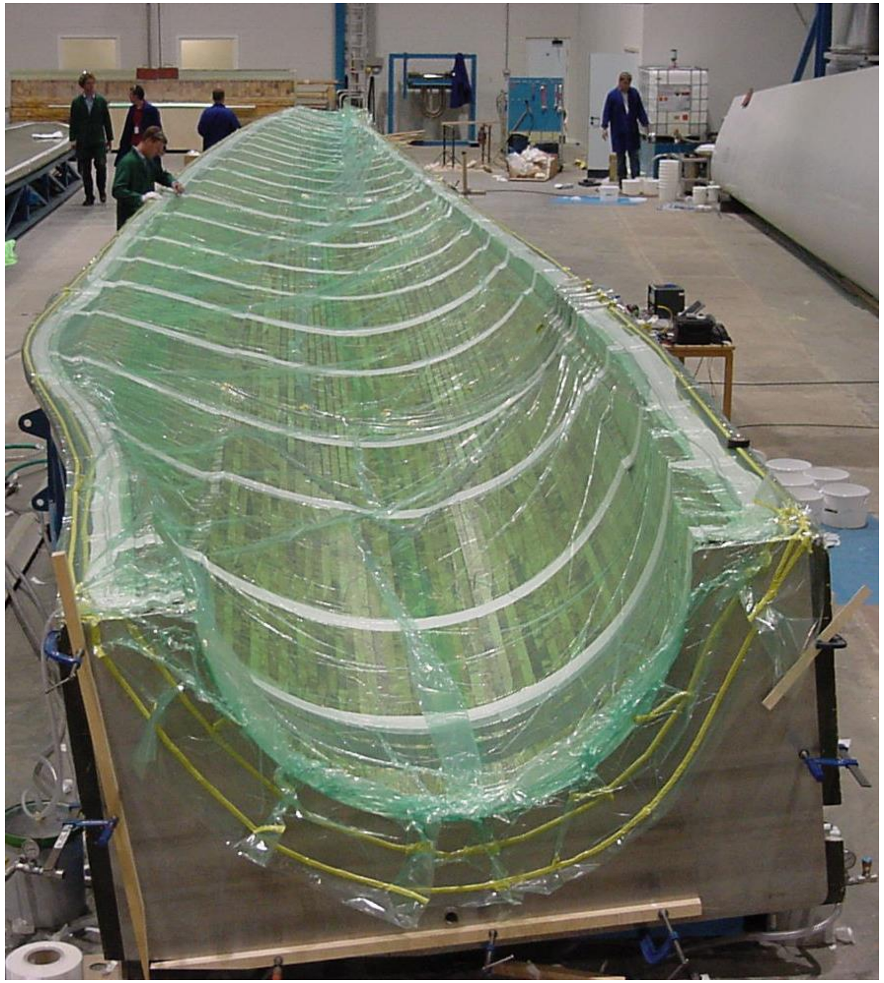




1. *Kołnierz aluminiowy*
2. *Rura kompozytowa (GFRE)*
3. *Liner polimerowy*
4. *Płaszcz z gumy silikonowej*



Inny przykład użycia kompozytów w sektorze Energii (struktura nośna)



Internal

2. Kompozyty włókniste

Materiały kompozytowe

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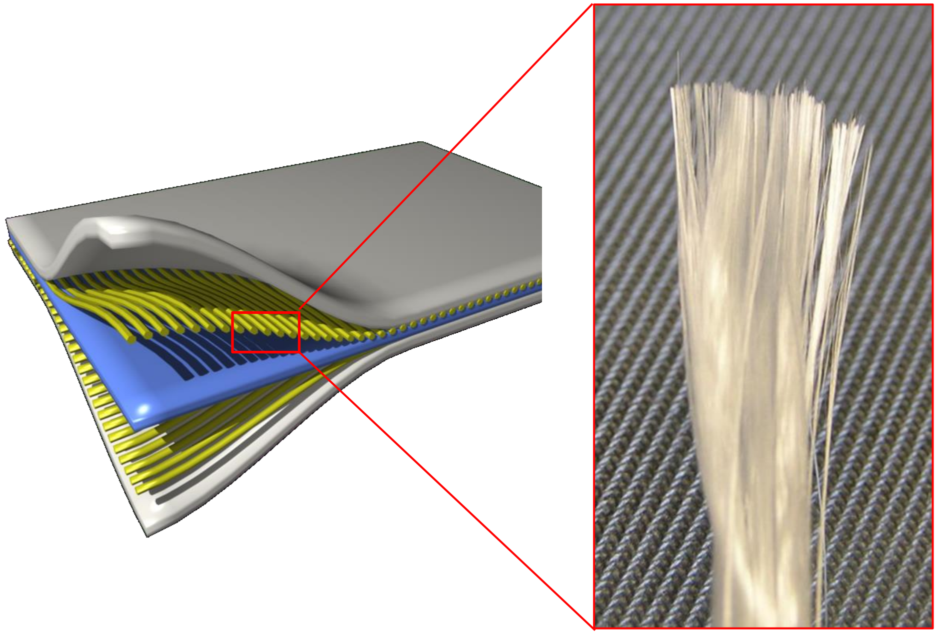
KOMPOZYT

- System składający się z dwóch lub więcej fizycznie odrębnych komponentów (faz),
  których połączenie powoduje powstanie właściwości materiałowych różniących się (lepszych) od właściwości składników.

1. Osnowa (*np. polimer, żywica epoksydowa, ...*)
   – zapewnia stabilność i ochronę faz przed działaniem środowika, transferuje naprężenia mechaniczne, spowalnia proces starzenia
2. Faza wzmacniająca (*np. włókno szklane / węglowe / aramidowe (kevlar) / bazaltowe, a także cząsteczki kwarcu, krzemionki, szkła, ...*)
   - znacznie poprawia wymaganą cechę materiałową, np. wytrzymałość

Rodzaje kompozytów

- zbrojone włóknem (włókna długie / krótkie)
- umacniane cząsteczkami (domieszkowawne / dyspersyjne)
- strukturalne (laminaty / „plastry miodu”)



Wady

- Anizotropia własności
- Wytwarzania jest czasochłonne, często ręczne i kosztowe

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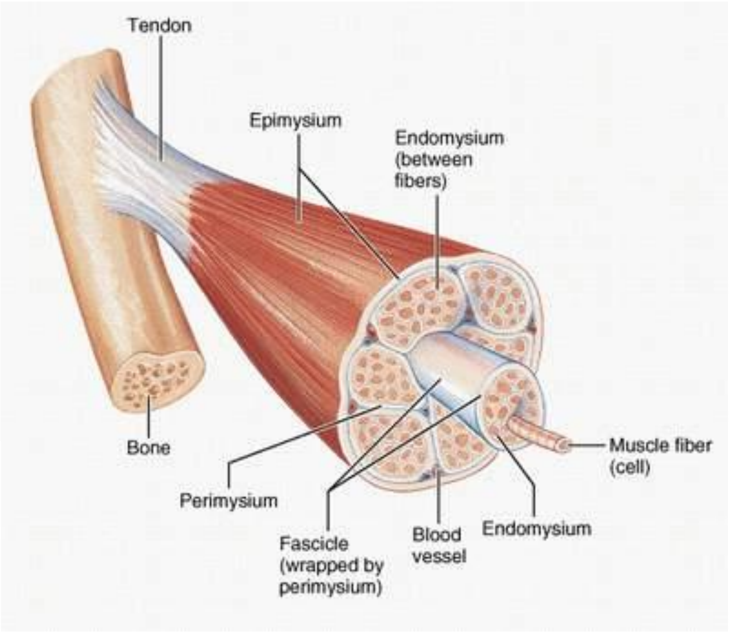
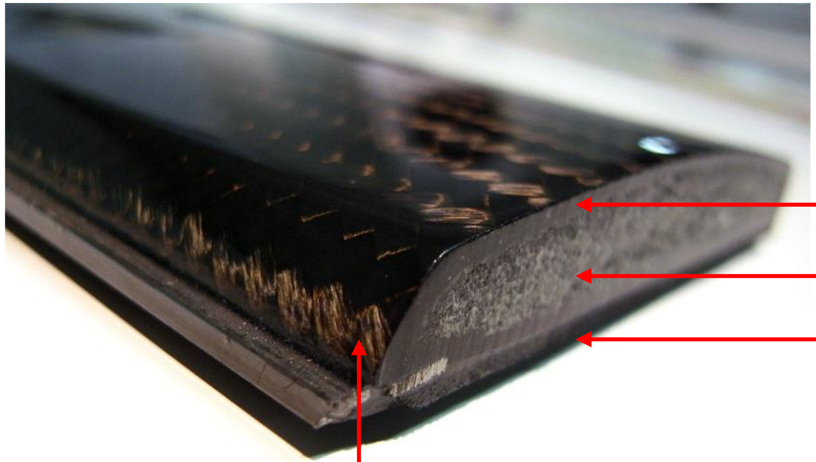
Najbardziej złożony materiał kompozytowy, jaki znamy



cross section of a bundle
of nerve fibers

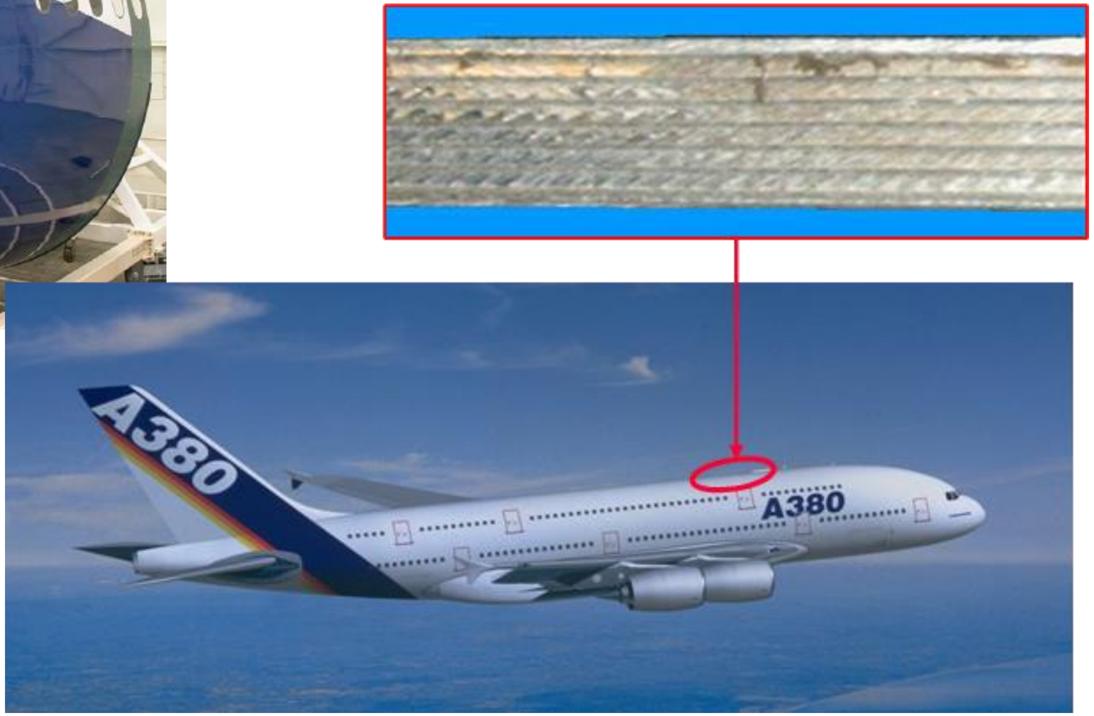
Sprzęt sportowy

Przekrój narty



Internal

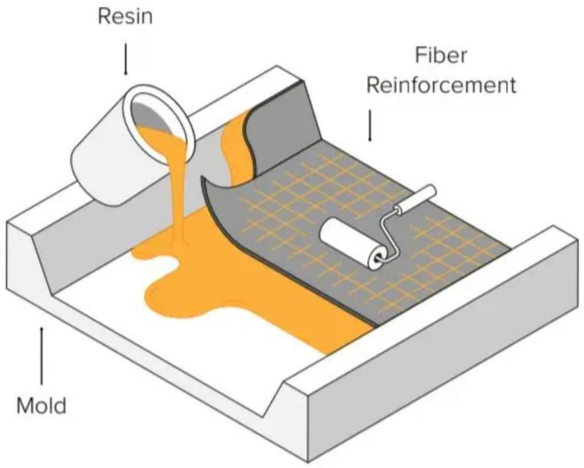
Zbiorniki, struktury ciśnieniowe, transport lotniczy

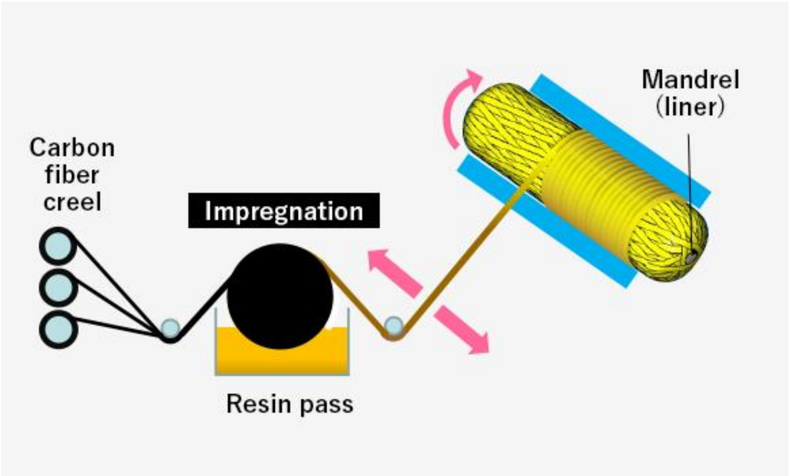


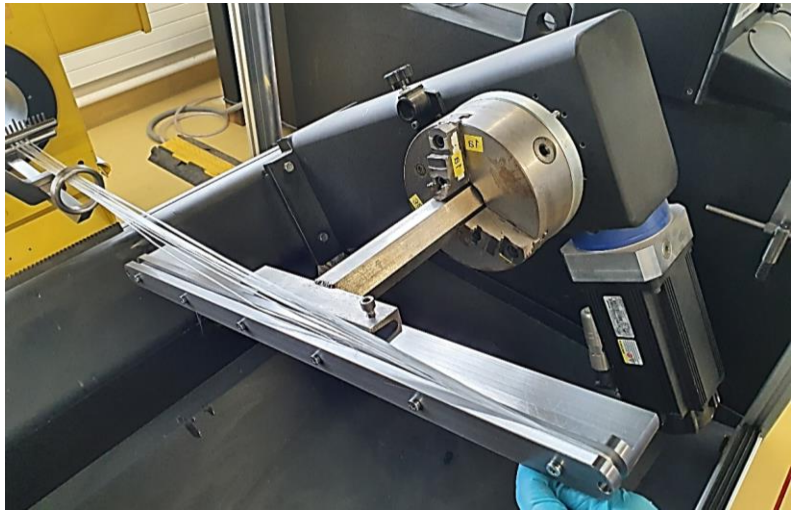
Internal

Wzmocnienia elementów strukturalnych

Proces produkcyjny - schemat



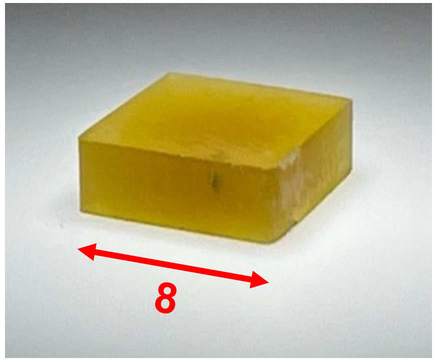


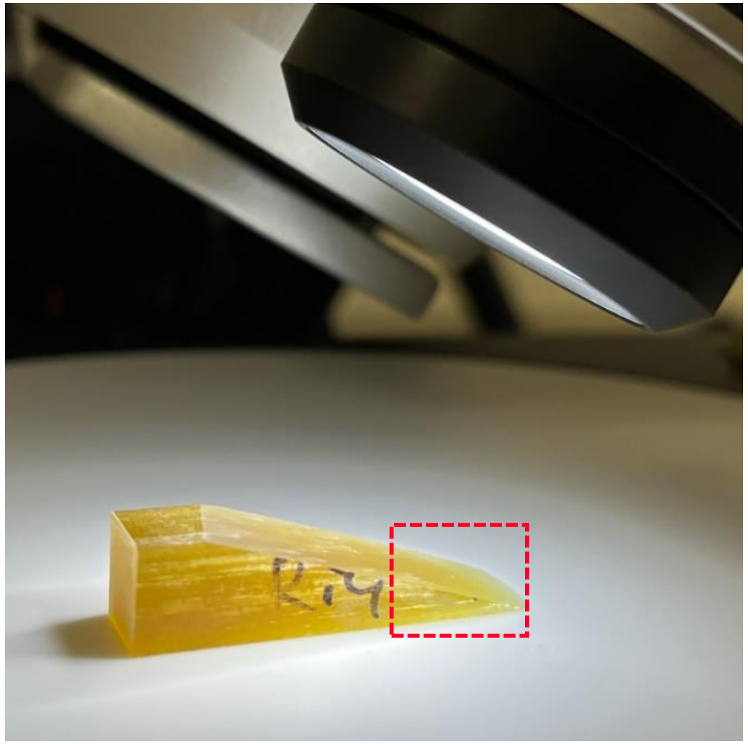


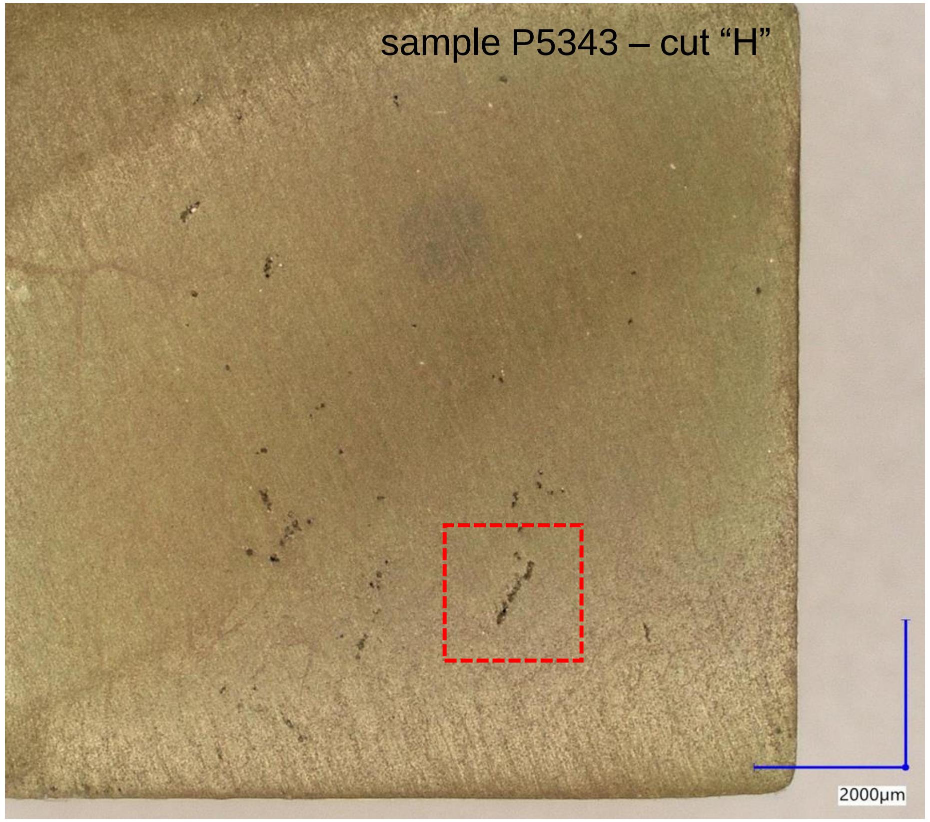
Ocena jakości procesu produkcyjnego

- Microscopic Analysis (destructive testing)
- Computerized Tomography
- Ultrasonic Testing

- Keyence VHX-7000 series (samples cut and polished / 2500 grit)
- Nikon XT H 225 ST
- Olympus OmniScan X3 / 5L64 transducer / immersed TFM







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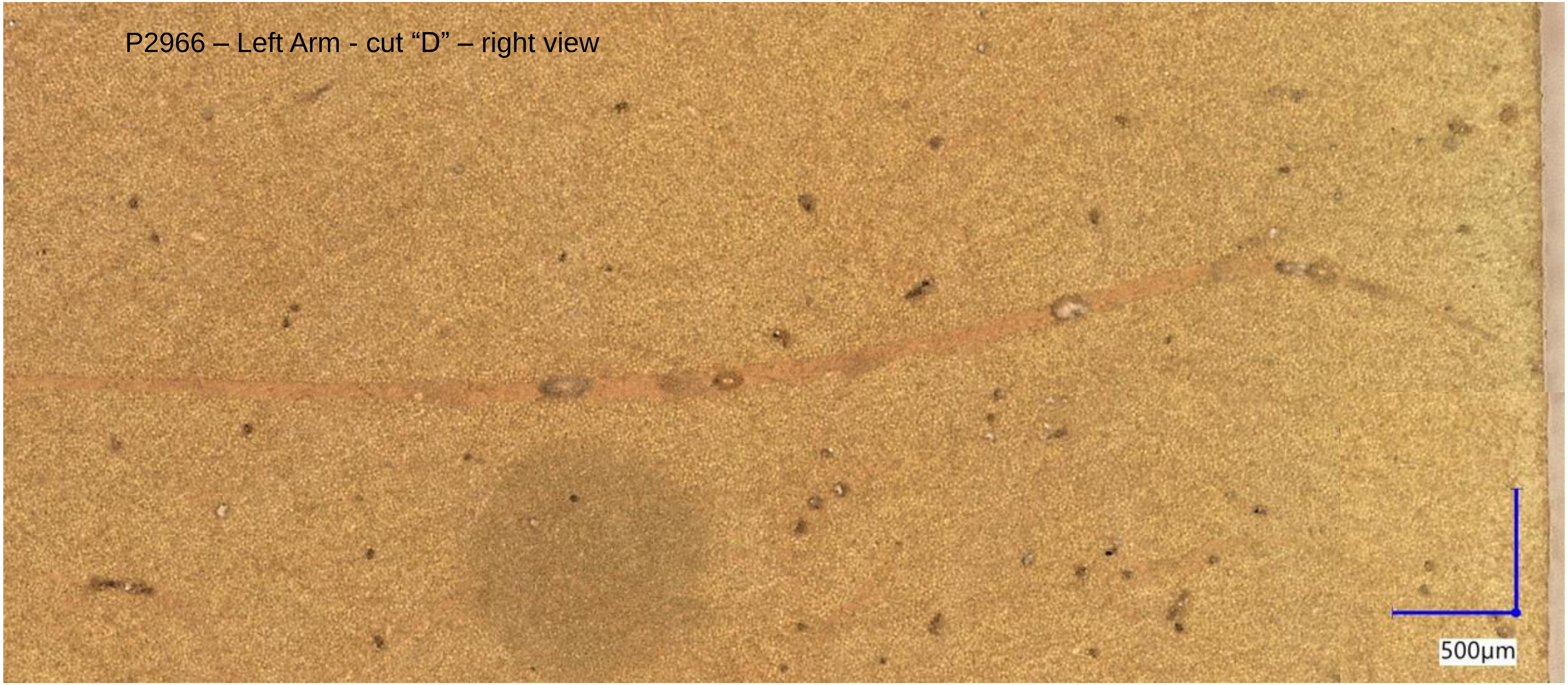
Możliwe wady w procesie produkcji: pustki powietrzne – źródło PDs



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Schemat formowania pustek powietrznych (I)

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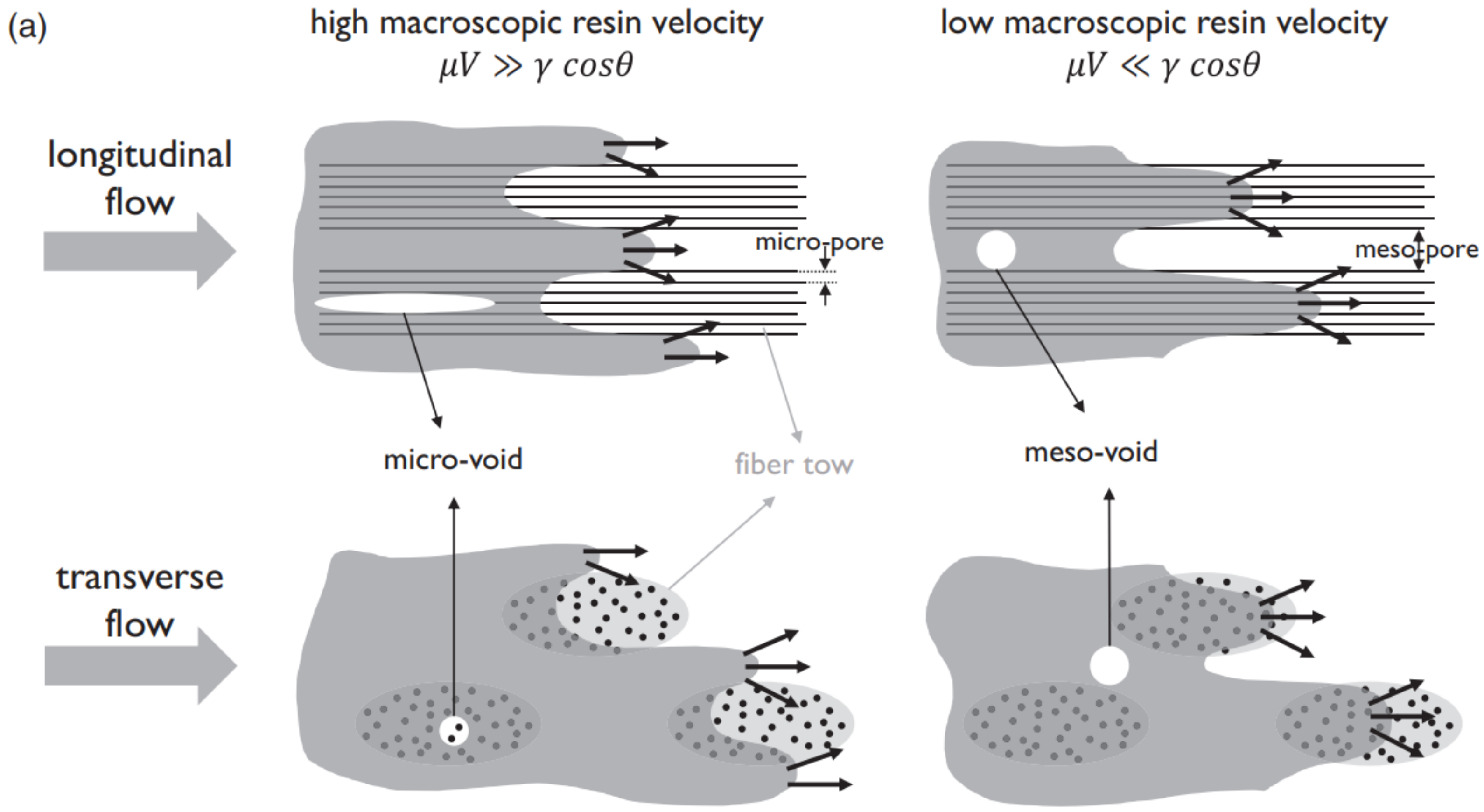

Przepływ wiskotyczny vs. kapilarny

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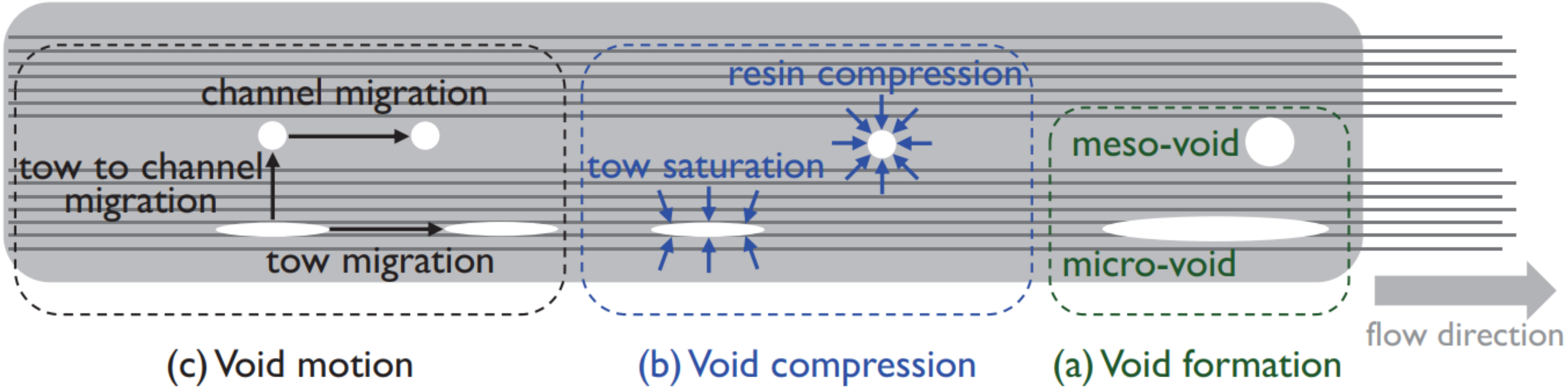
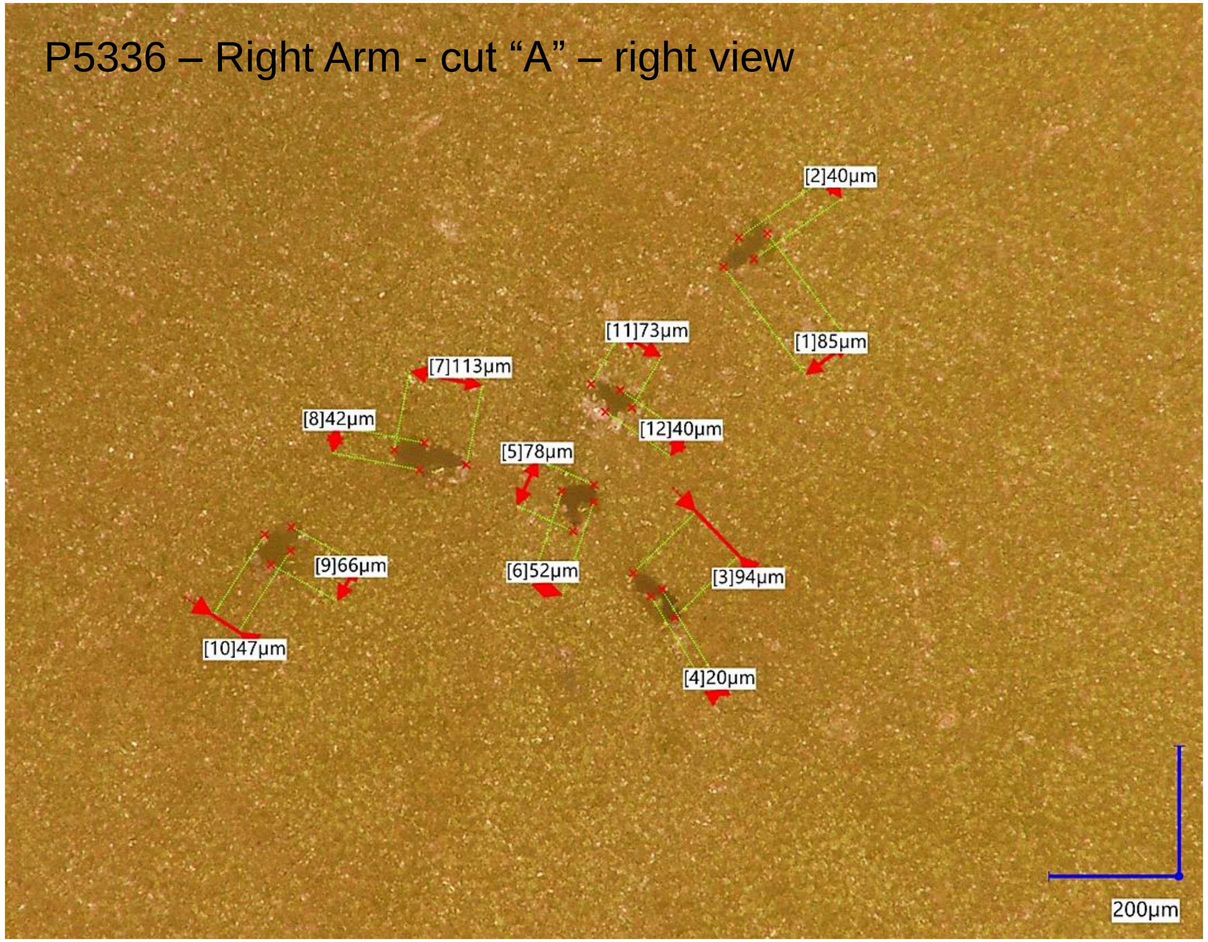
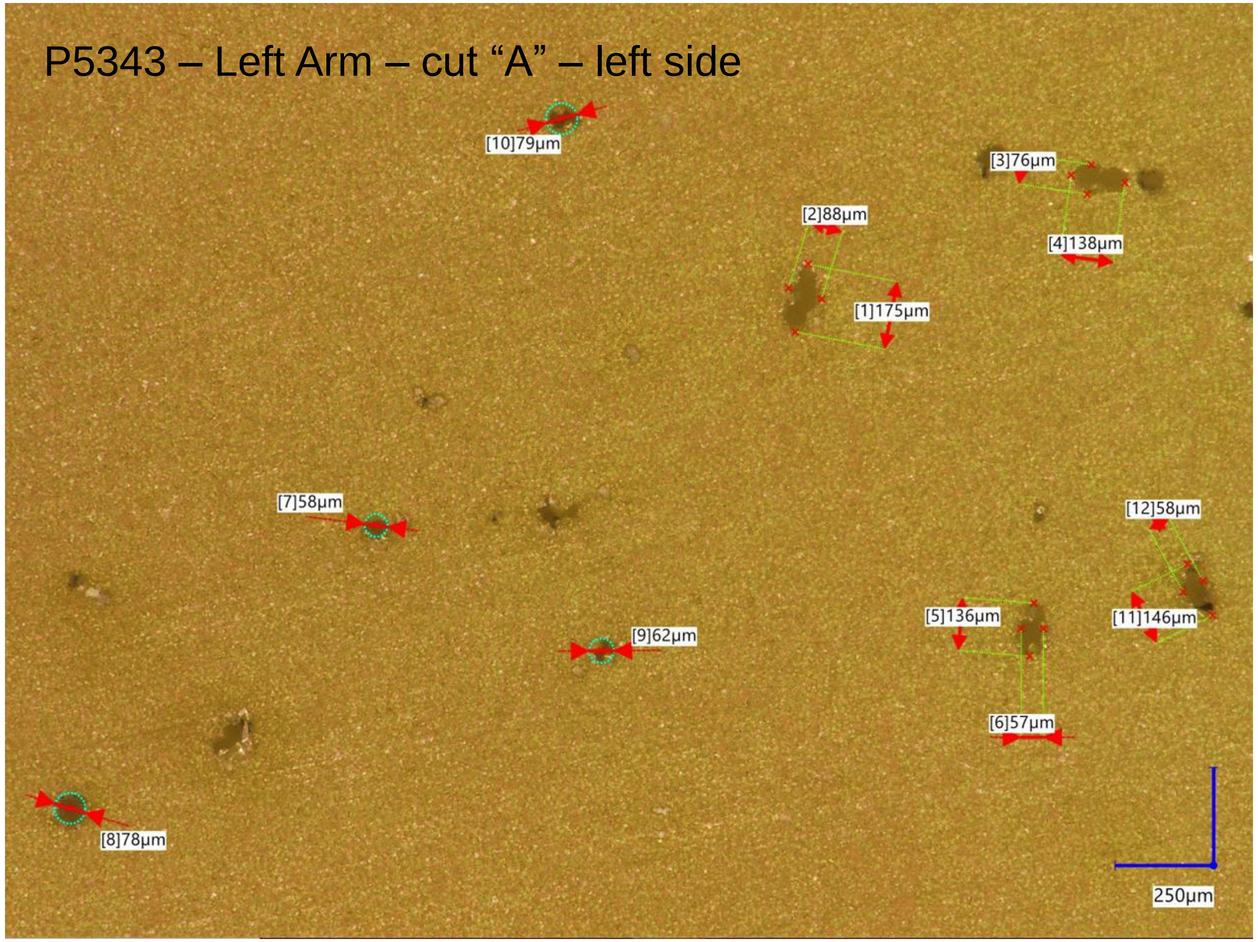
Schemat formowania pustek powietrznych (II)



Impregnacja żywicy – 3 fazy tworzenia pustek

Typowa wielkość pustki <200 um (dla konkretnej grupy produktowej)





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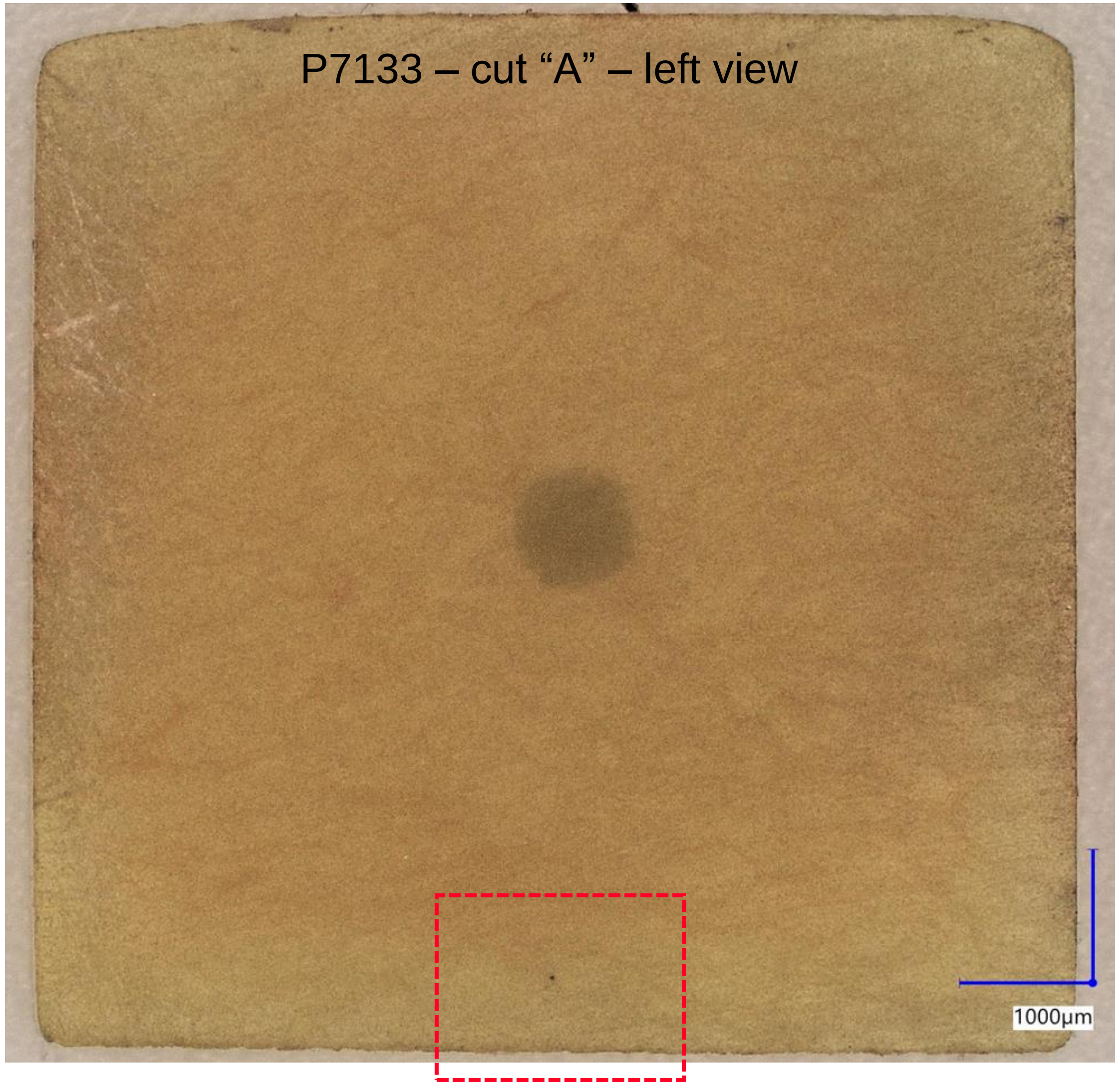
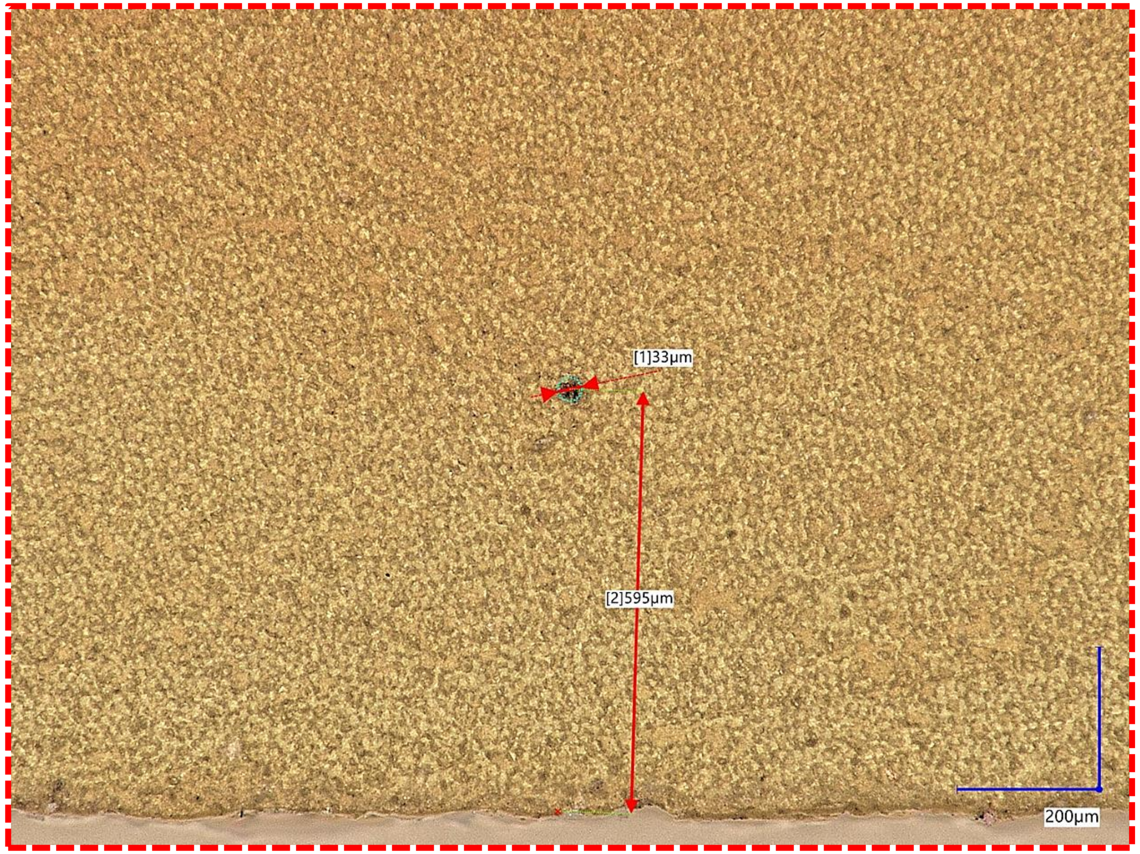
Nawet bardzo dobre jakościowo wyroby mogą mieć pojedyńcze wady





- Wada niewykrywalna przez CT

-

Nieniszczące metody inspekcyjne *

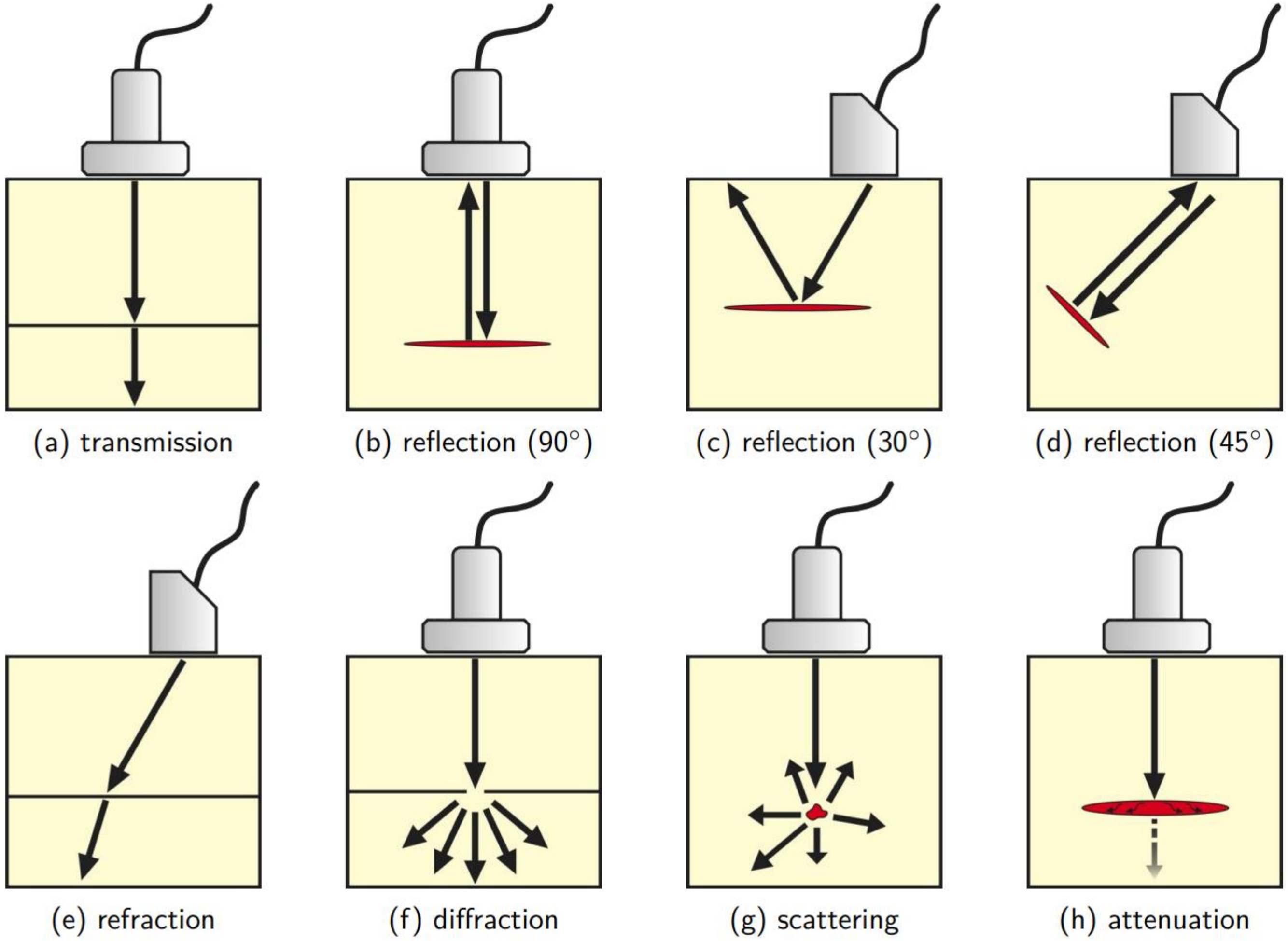
	Visual	Through-transmission	Shearography	Pulse-echo	Velocity	Low frequency	Radiography	Acoustic emission	Thermography
Flaw sought									
Fibre type					●				
Porosity	●	✓		✓	●				
Fibre-matrix bond	●							●	
Matrix properties				●	●				
Fibre misalignment		●				●	●		
Volume fraction		●		✓	●	●	●		
Stacking sequence									
Ply-end discontinuity				●					
Foreign inclusions		●	●	✓			✓		✓
Trans-laminar cracks		●	✓	●			●	✓	●
Fibre breakage								✓	
Delamination	✓	✓	✓	✓		✓	●	✓	✓
Moisture ingress					●				
Impact damage	✓		✓						✓

● Application limited
✓ Method has proved ability to detect given flaw

* *Non-destructive testing of composite materials*, by National Composite Network

3. Technika ultradźwiękowa

Przykłady podstawowych interakcji fali dźwiękowej



* *Non-destructive evaluation of composite aircraft elements based on ultrasonic testing and image analysis*, by Katunin

Zasada działania: A-skan

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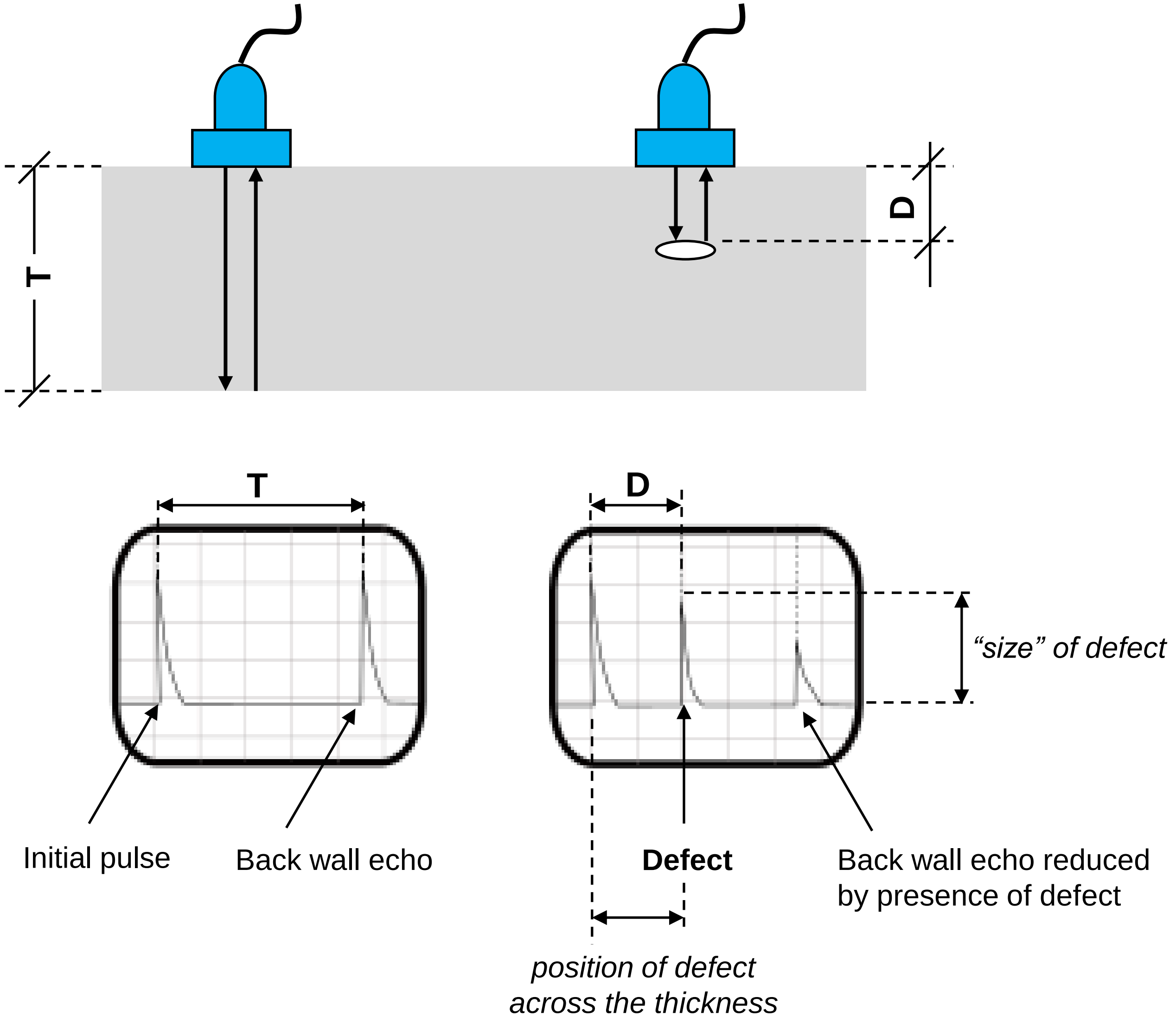

A-scan:
display of the ultrasonic signals in which the **one axis** represents **time** and the **second axis** represents **amplitude**

- **The time delay** between the initial pulse and the defect indication defines the relative position of the flaw.

  The **depth of the defect** is determined by the ratio **D/T**

- The **amplitude** (strength) of the signal represents the **intensity of the reflection**.

  It can be calibrated to the **"size" of the defect**, using reference holes (with known diameters)

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Zasada działania: B-skan

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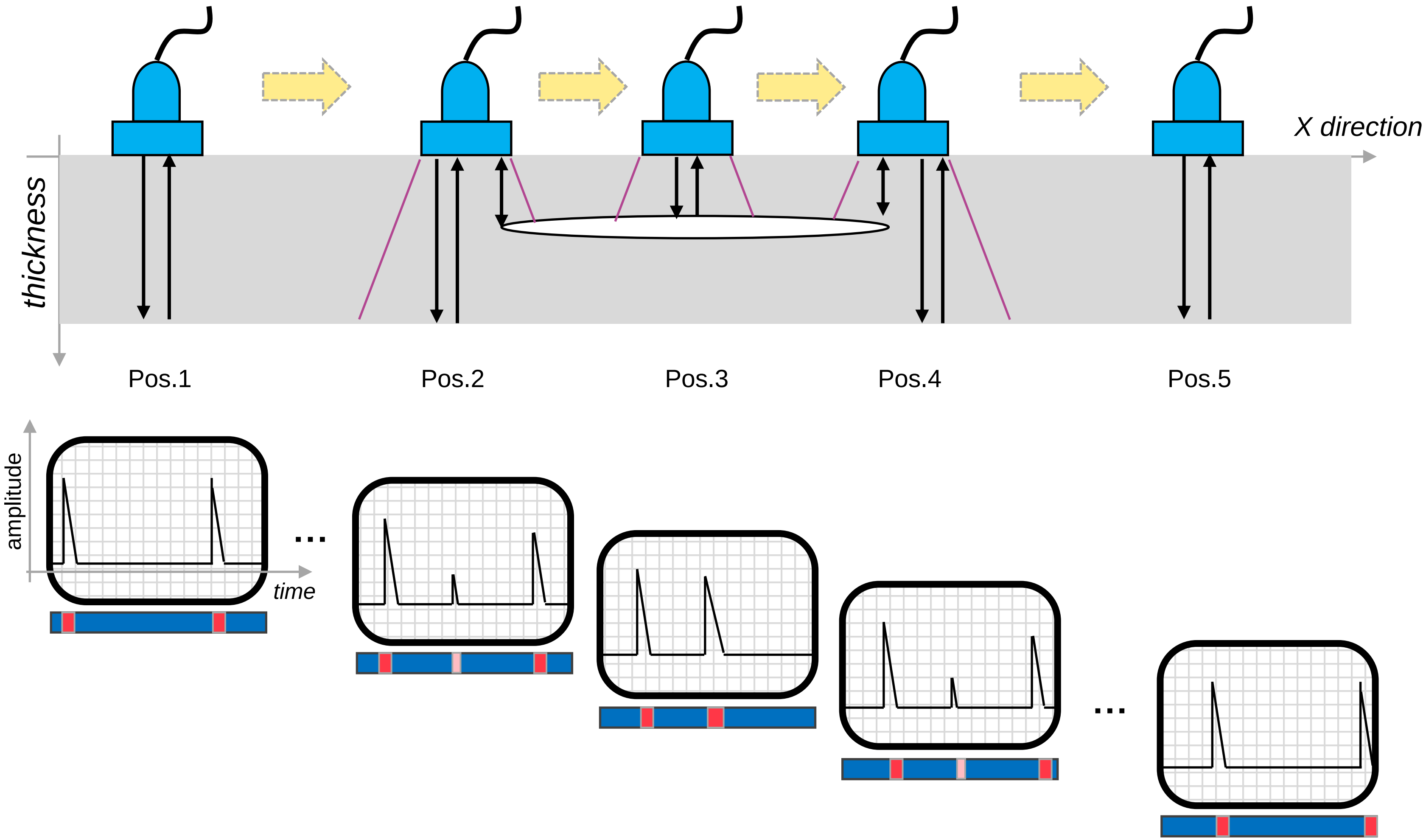

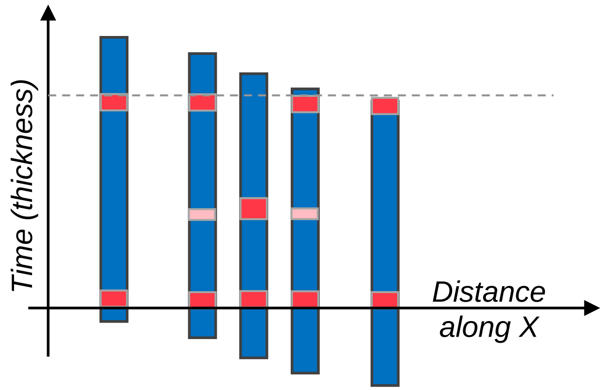

B-scan:
display of the ultrasonic signals in which
one axis represents **time** and
the **other axis** represents **distance**, and
the **amplitude** of signals is represented by **color**

- **The time delay** between the initial pulse and the defect indication defines the position of the flaw.
- The **amplitude** (strength) of the signal which represents the intensity of the reflection, is coded **as color**.
- Simplified, color-coded A-scans are plotted along the distance

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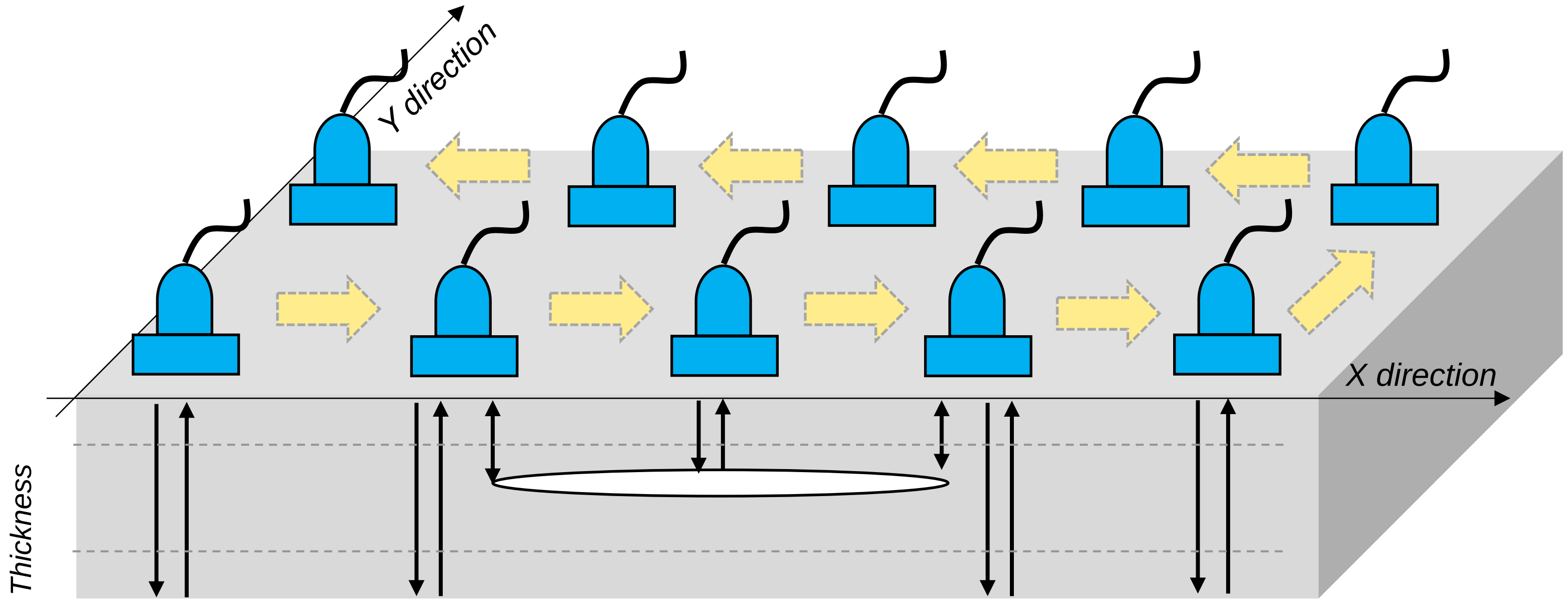
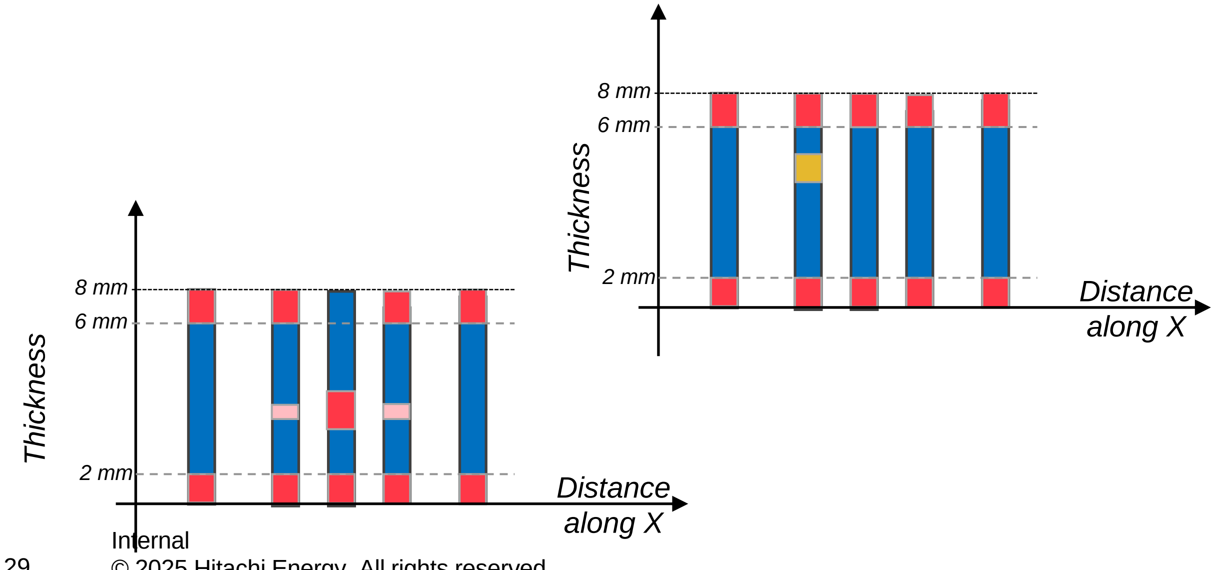
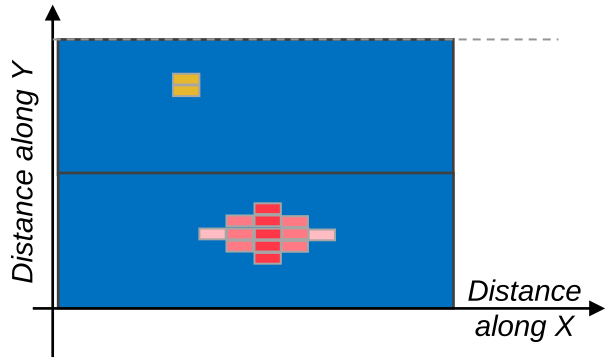
Zasada działania: C-skan







C-scan:

display of the ultrasonic signals in which **both axes** represent **distances** on the scanning surface, where the **amplitude** of the signals **within a defined time window** is represented by **color**

- The **amplitude** (strength) of the signal which represents the intensity of the reflection, is coded **as color**.
- A **defined time window** limits the analyzed thickness of the object (**e.g. from 2 to 6 mm**).
- Colored B-scans are plotted along the second axis.

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Klasyczna technika ultradźwiękowa – ograniczenia przemysłowe

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- Badanie izolacji elektrycznej wymaga wysokiej czułości metody (< 0.7x0.7mm)
- Duże tłumienie sygnału w materiale kompozytowym ➔ ograniczona głębokość badania
- Automatyzacja procesu skanowania / kompensowanie nierówności powierzchni próbki
- Procesowanie olbrzymiej ilości (zaszumionych) sygnałów / automatyzacja przepływu danych
- Lokalizacja wad / wymiarownie / klasyfikowanie ➔ “Go / No Go”
- Konieczność stosowania medium sprzęgającego

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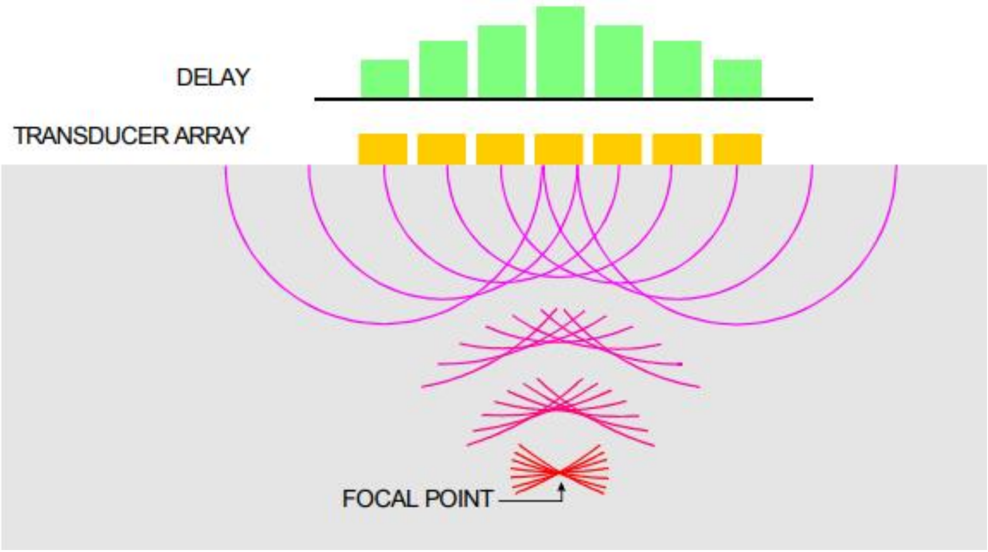
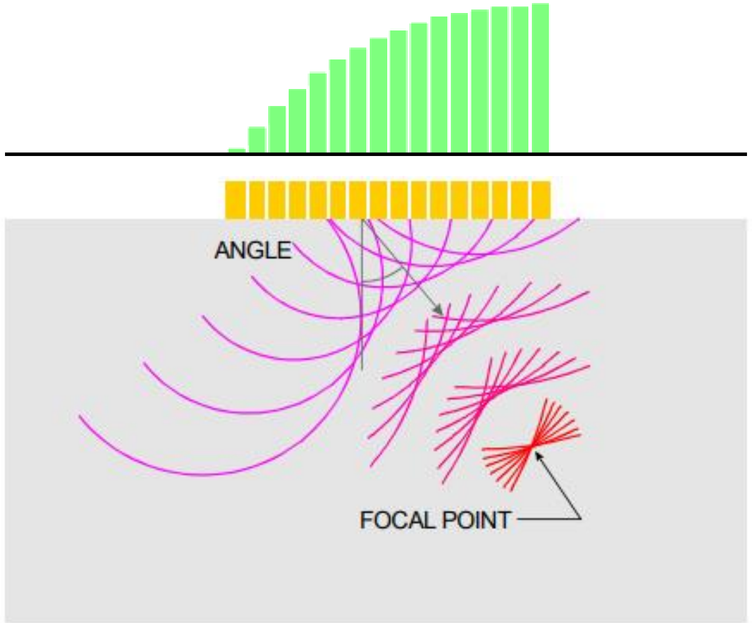
4. Beamforming

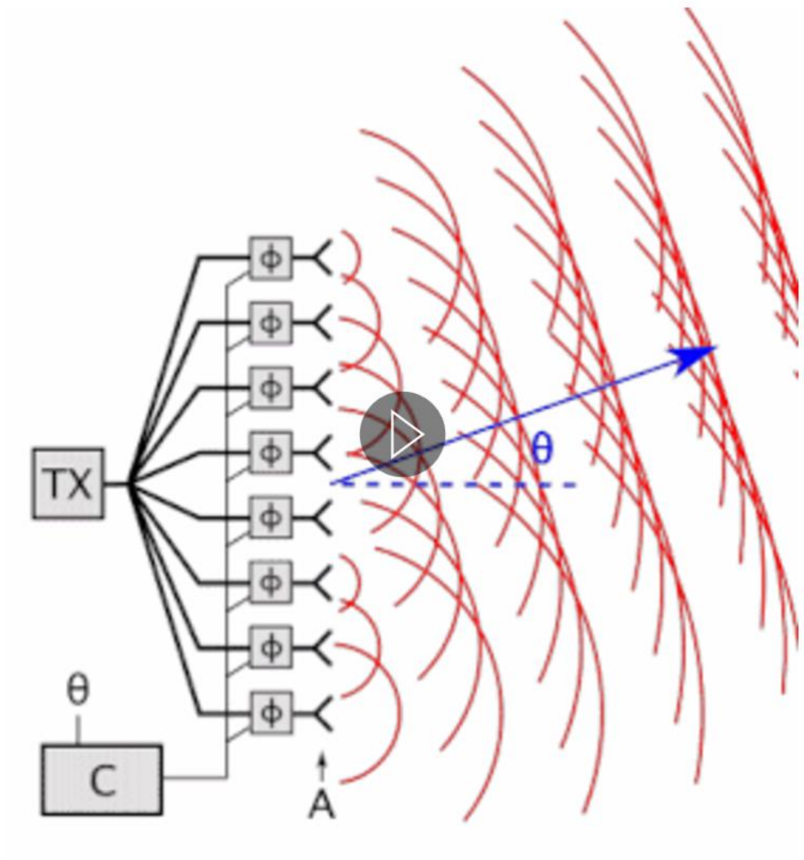
Phased Array method (physical beamforming)

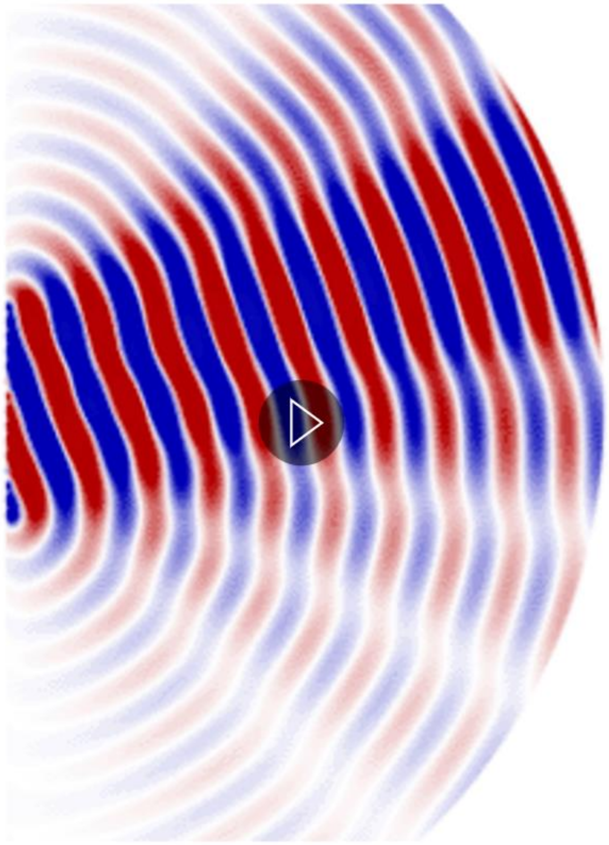
- multi-element probe
- phase shift
- physical beam-forming
- one focal point





Kształtowanie wiązki sygnału – zmiana fazy





Kształtowanie wiązki

Aplikacje: radar, sonar, medycyna, audio, MIMO Wi-Fi, 5G, satelity

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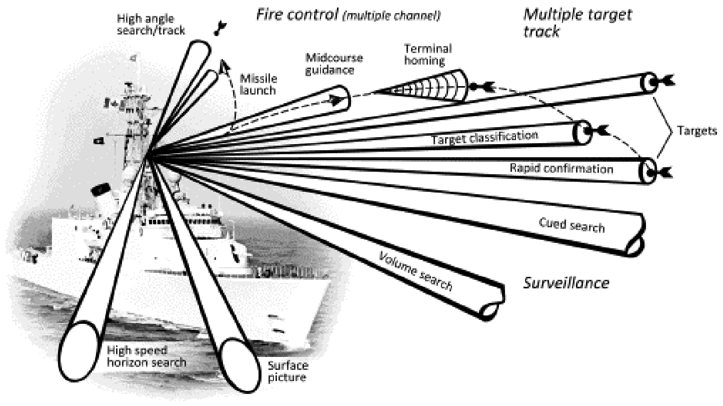

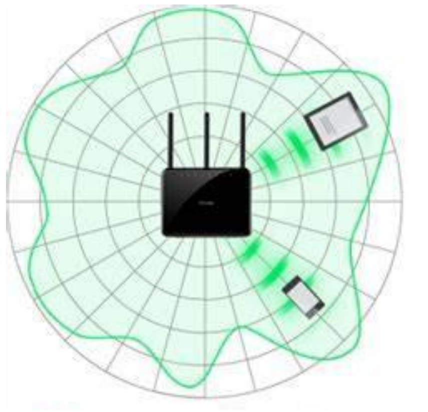

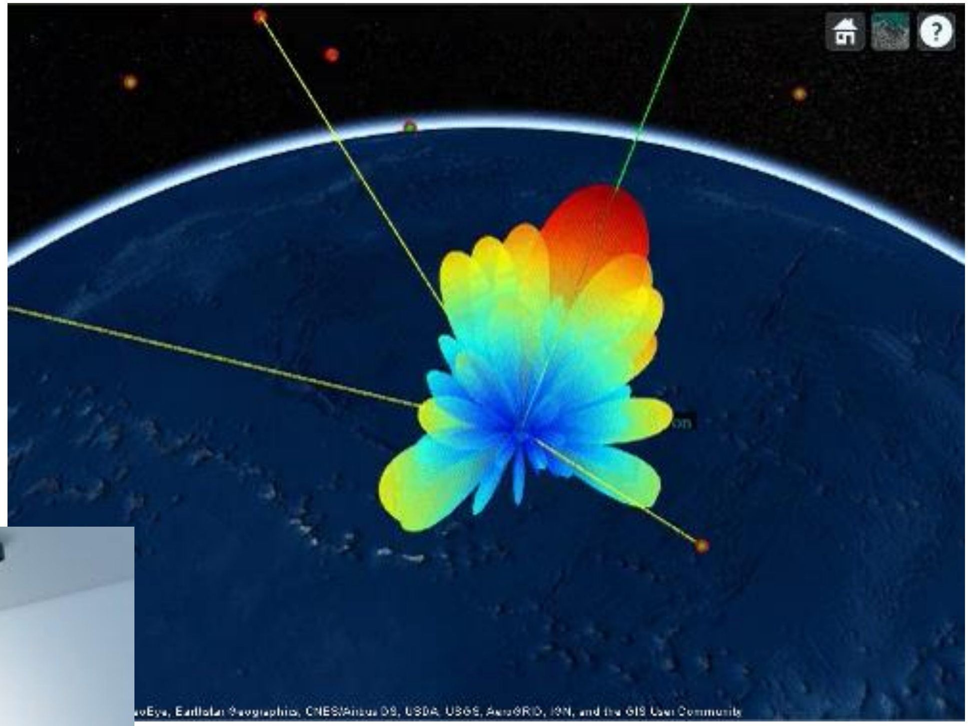

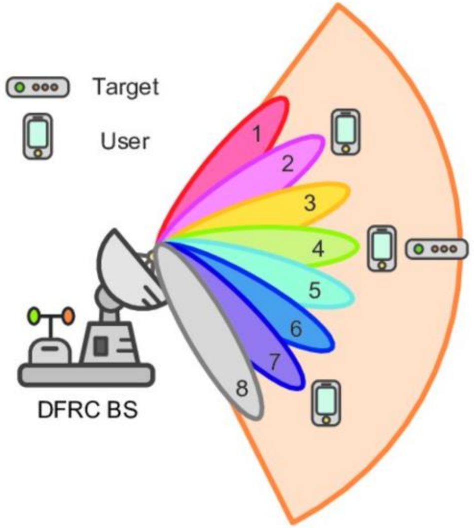

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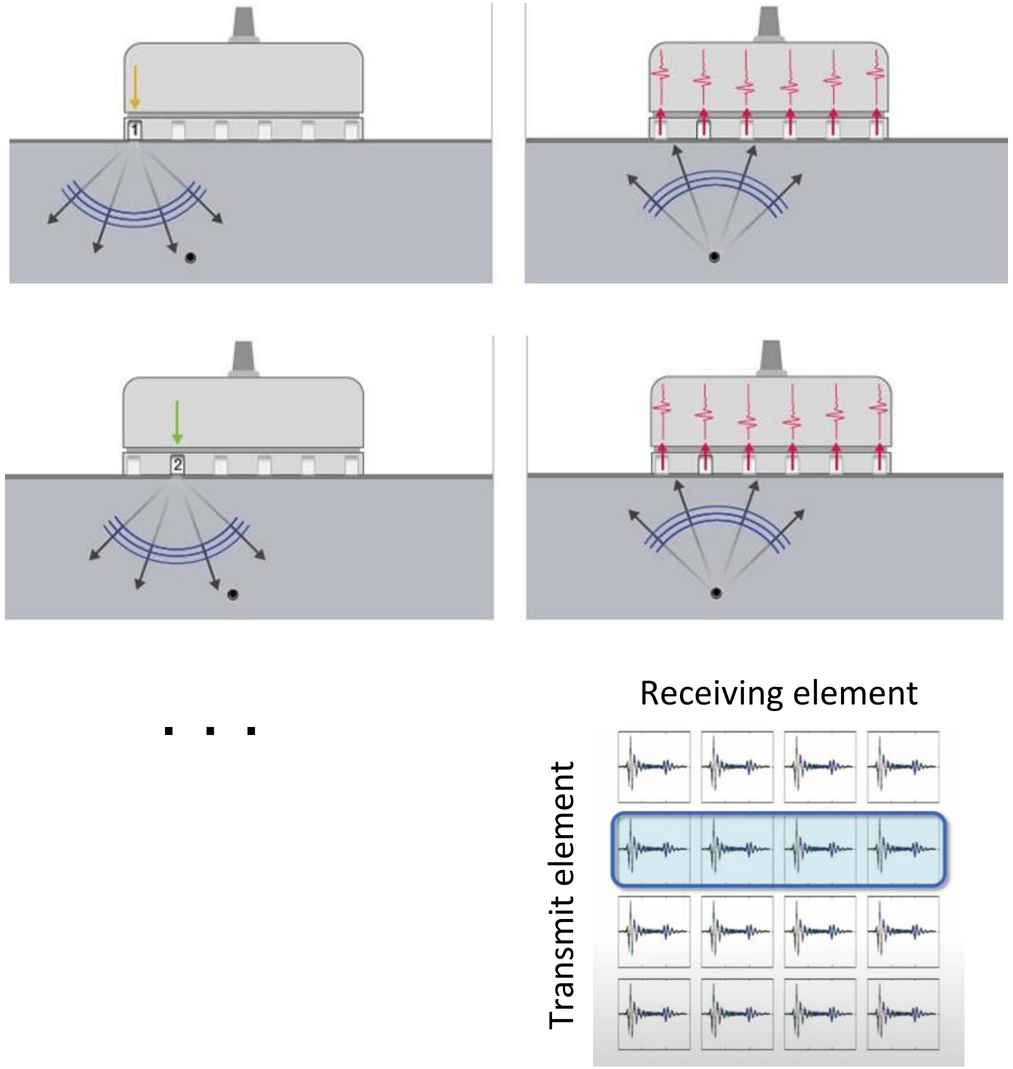
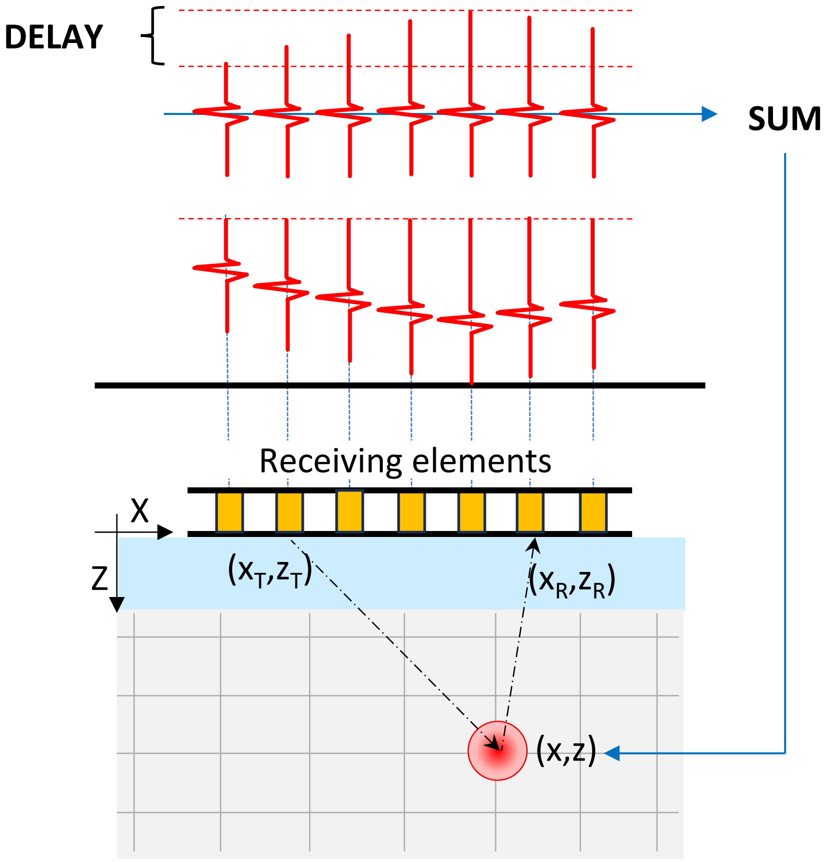
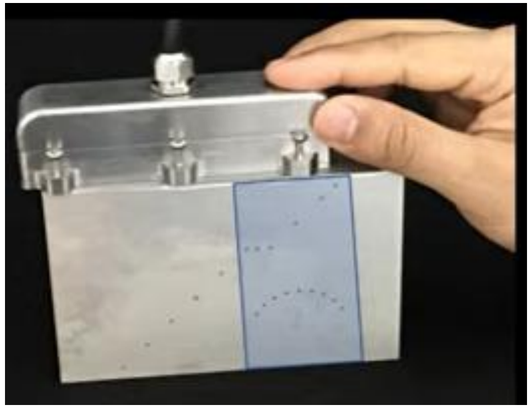
Total Focusing Method (digital beamforming)

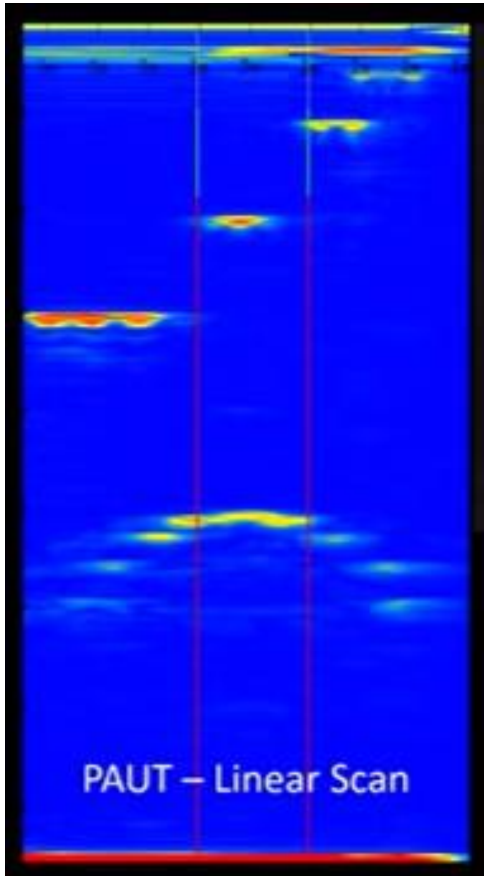


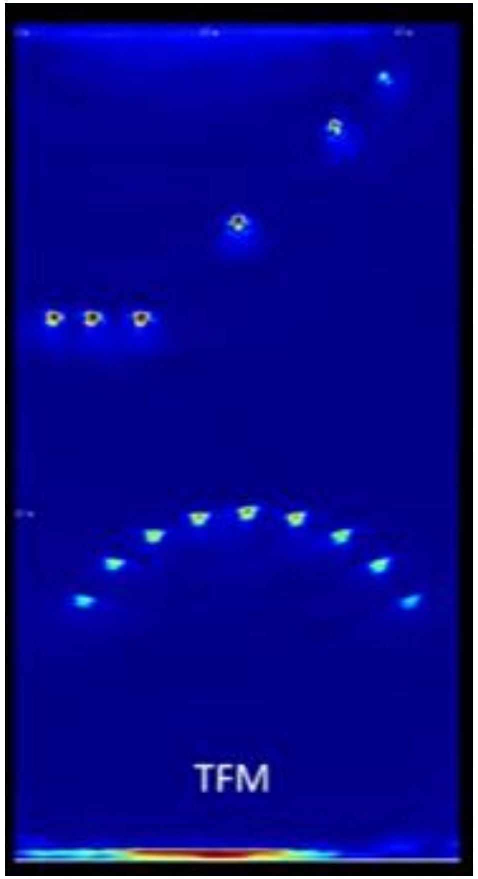


$$I(x,z) = \left|\sum h_{t_x,r_x}\left(\frac{\sqrt{(x_t-x)^2+z^2}+\sqrt{(x_r-x)^2+z^2}}{c_1}\right)\right|$$

Phased Array vs. Total Focusing Method





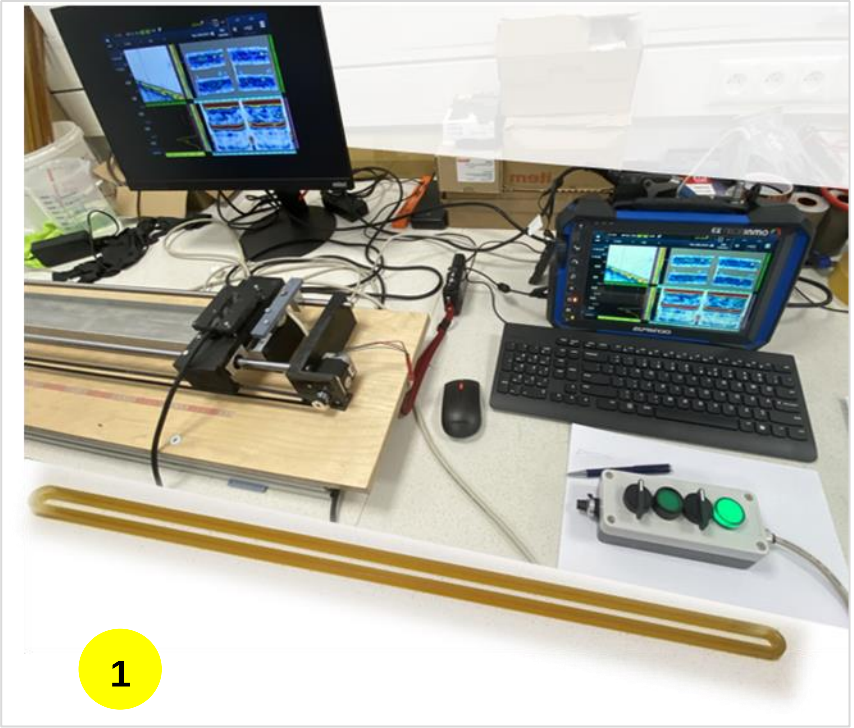


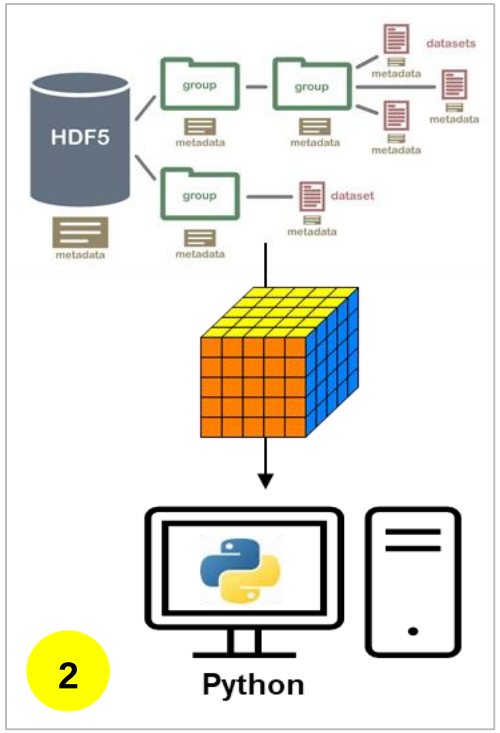
The Future of Phased Array Ultrasonic Testing: FMC / TFM

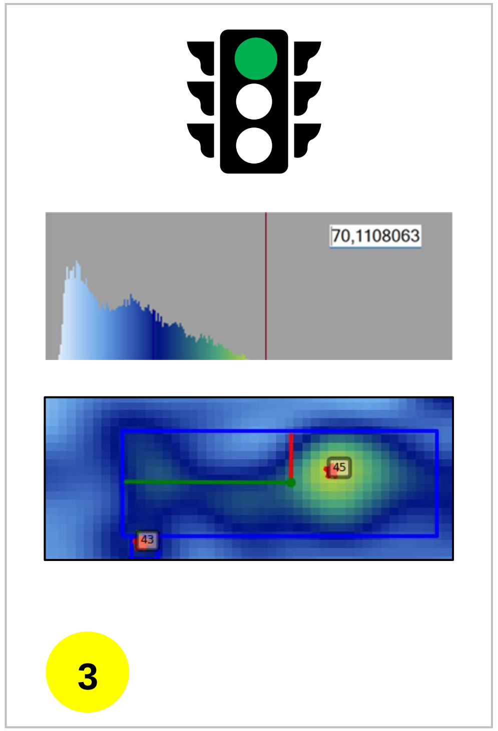
5. Aplikacja praktyczna

Koncepcja rozwiązania technicznego

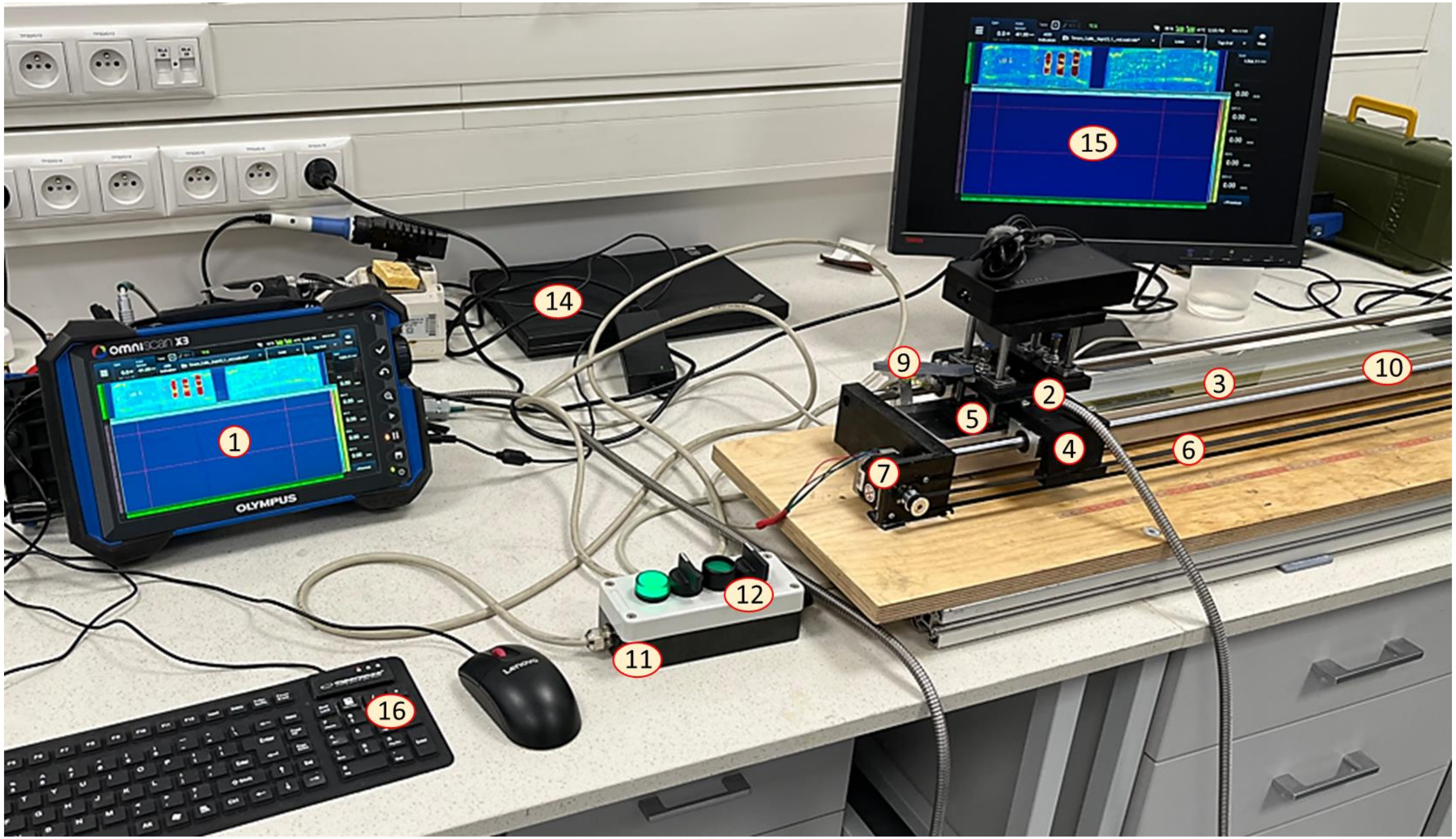
1. Rozwiązanie hardwarowe – szybkie skanowanie badanego obiektu (*water-immersed TFM*)
2. Rozwiązanie programistyczne – automatyczny procesing sygnałów ultradźwiękowych
3. Klasyfikacja produktu na podstawie liczby i wielkości zidentyfikowanych wad.







Rozwiązanie hardwarowe



1	Flaw detector
2	Transducer
3	Tested loop
4	Bridge
5	Spacers
6	Drive belt
7	Stepper motor
8	Encoder
9	End position sensors
10	Water tank
11	Automation controller
12	Direction selector
13	Data storage disk
14	PC with analysis software
15	Monitor (optional)
16	Keyboard & mouse (optional)

Proces skanowania ...

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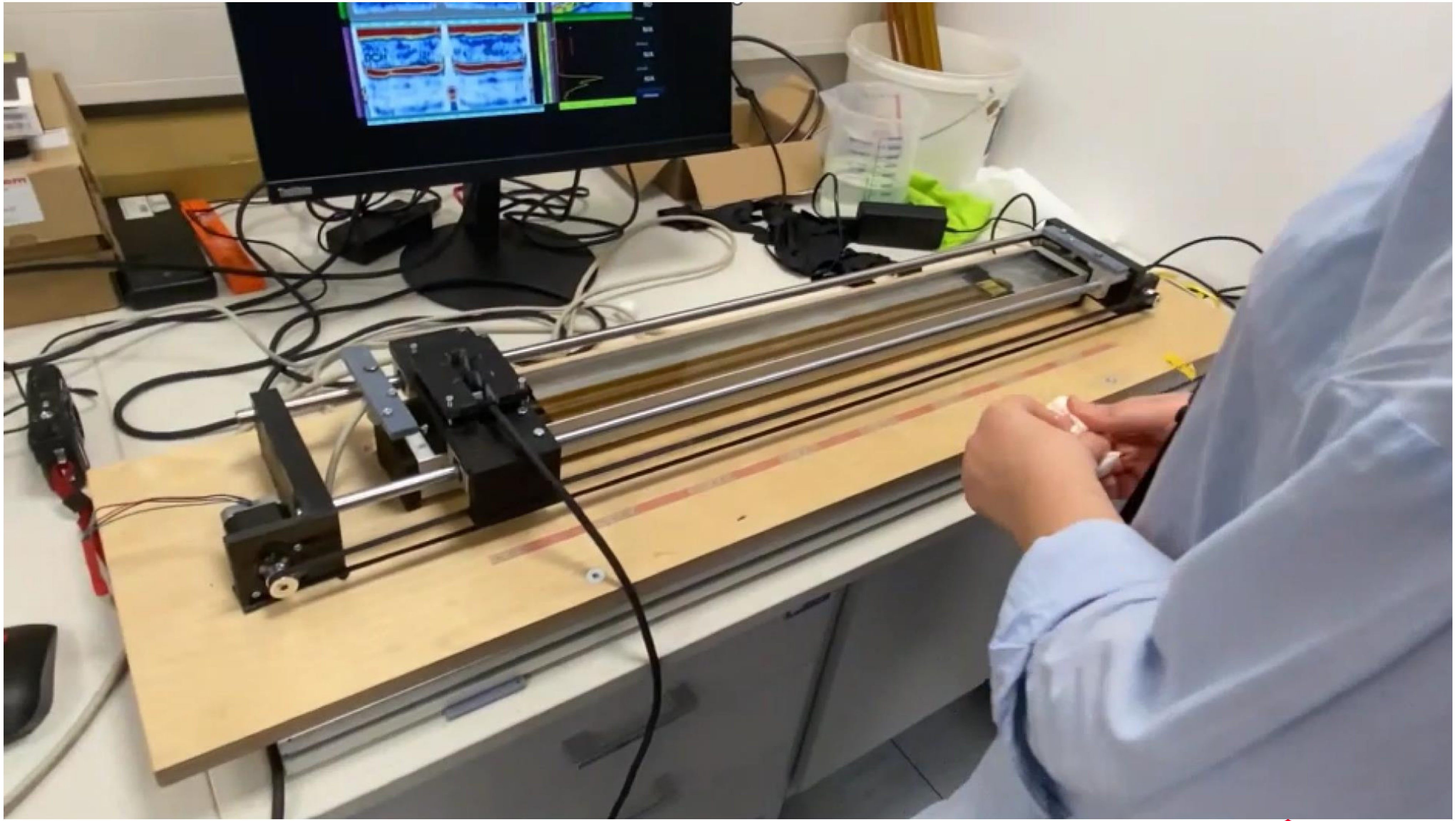

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Część programistyczna (Aleksandra Ziaja-Sujdak)

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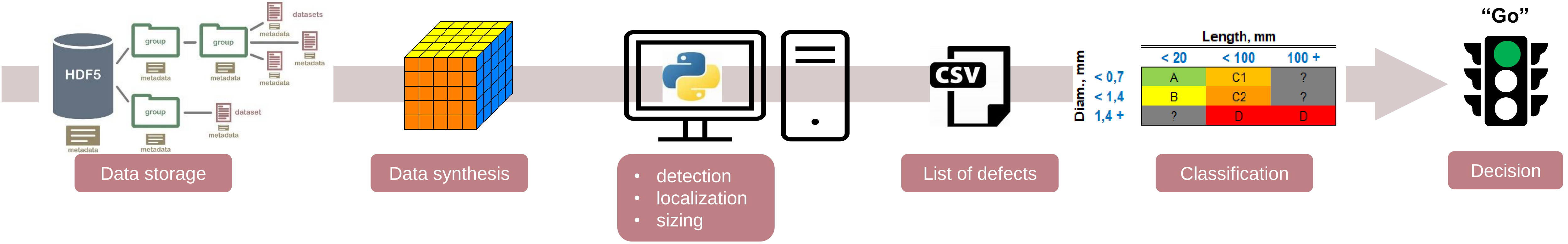

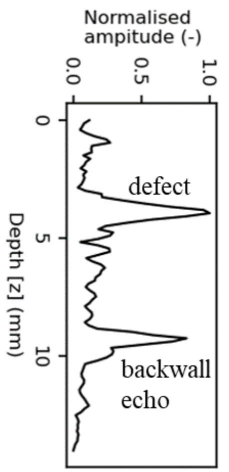

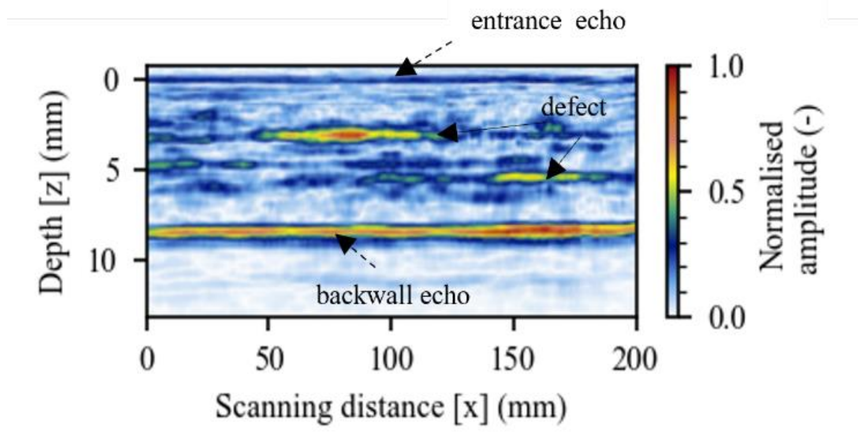

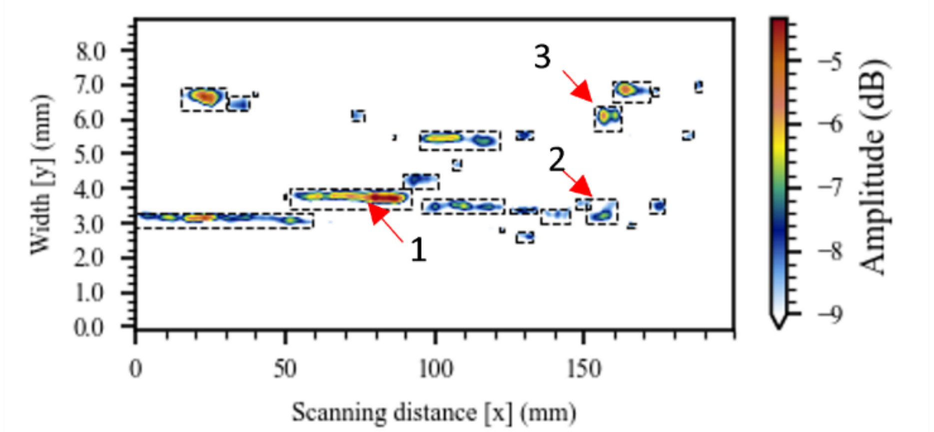

Defect id	Location x [mm]	Location y [mm]	Location z [mm]	Length x [mm]	Length y [mm]
1	80	3.8	3.7	69	0.6
2	156	6.0	7.2	16	0.7
3	156.5	3.2	3.9	30	0.4

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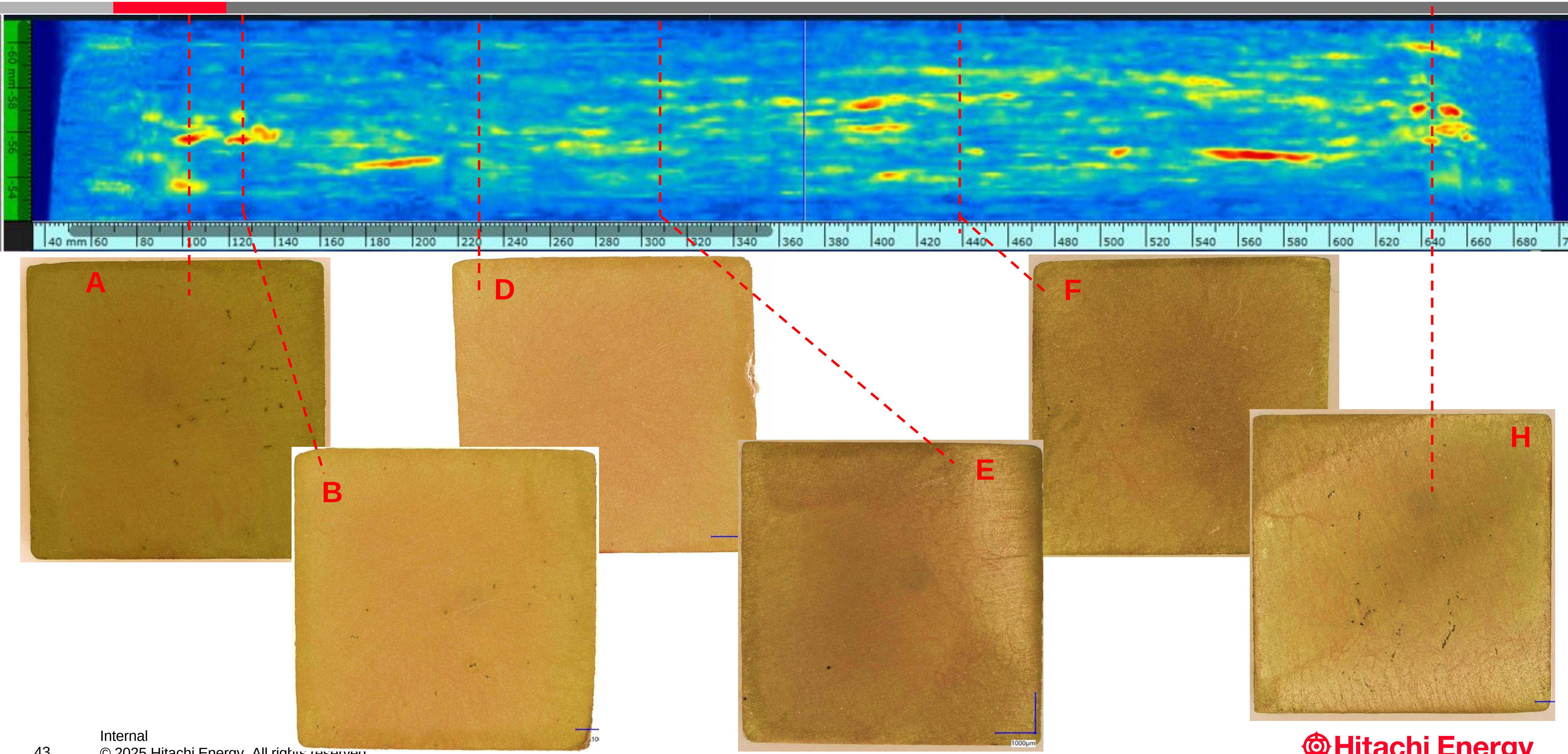
6. Wyniki

Walidacja metody: Analiza mikroskopowa vs. UT (P5343)



Internal

Validation Procedure – CT vs. Microscopic analysis

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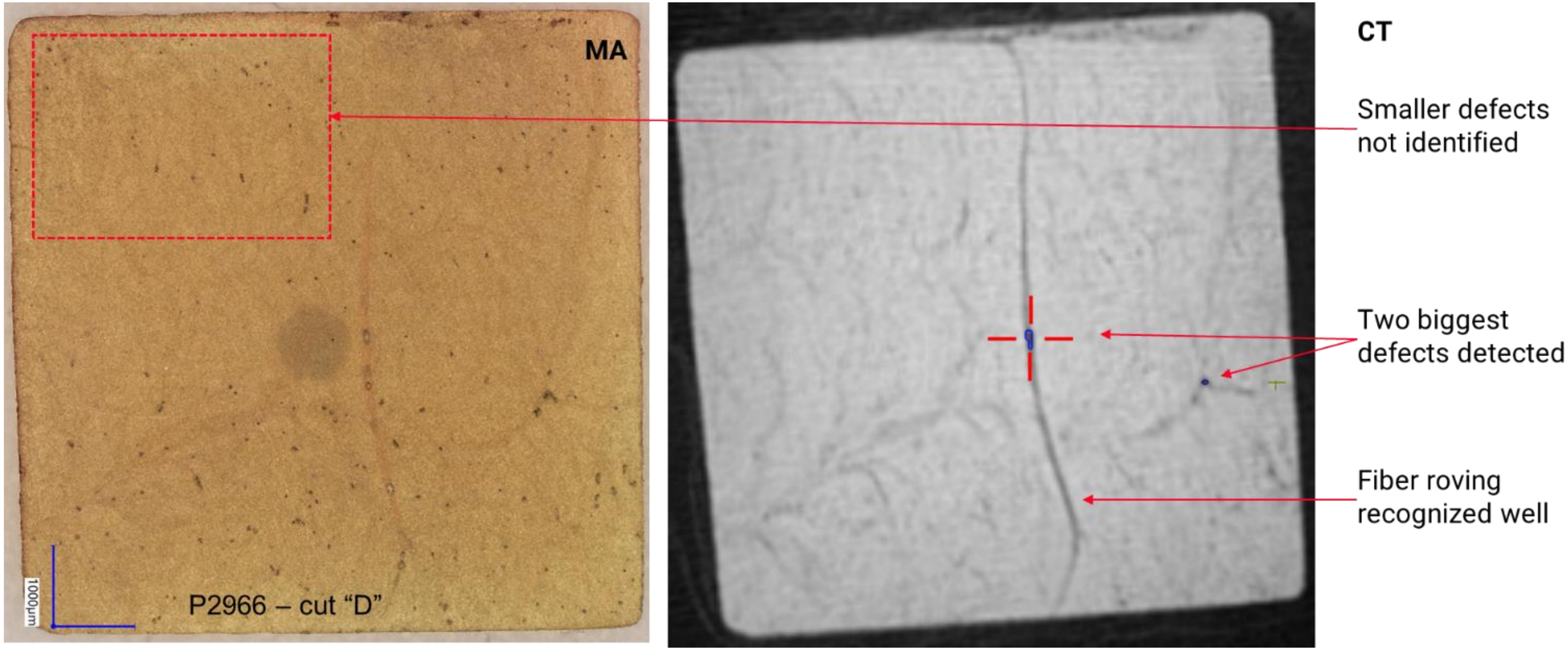

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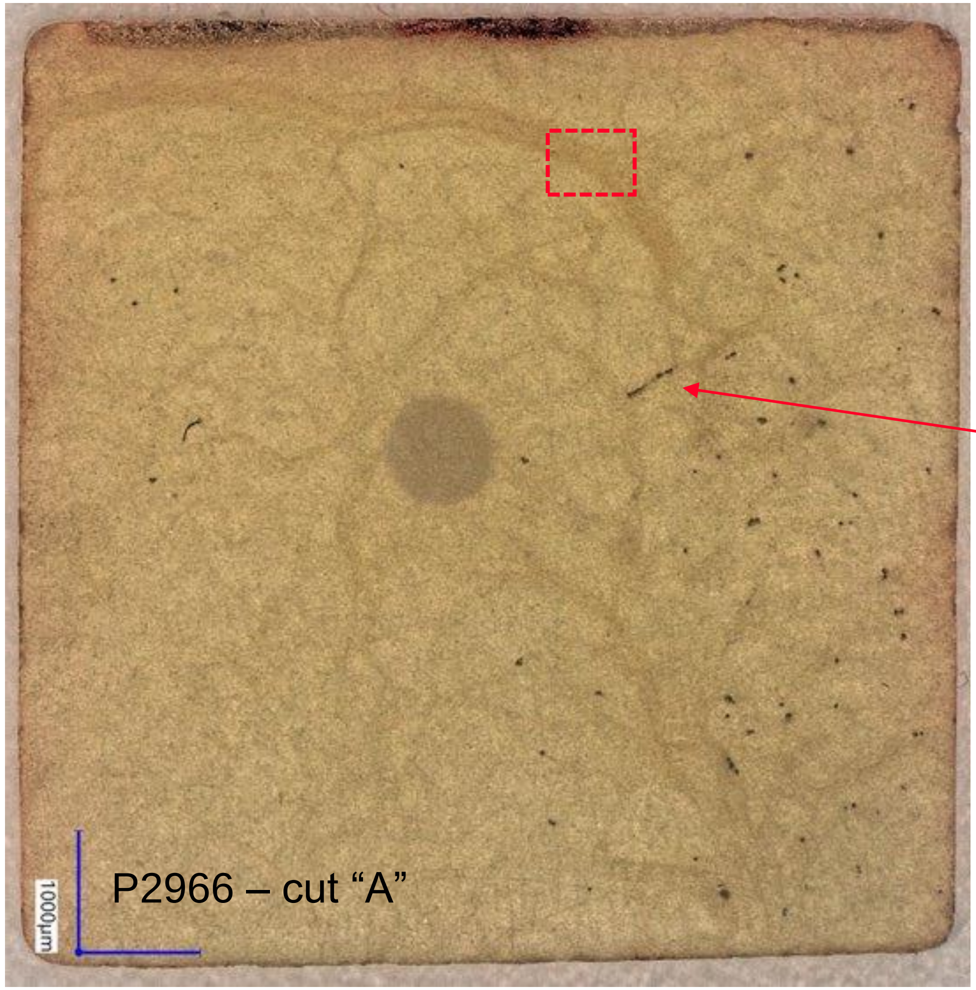
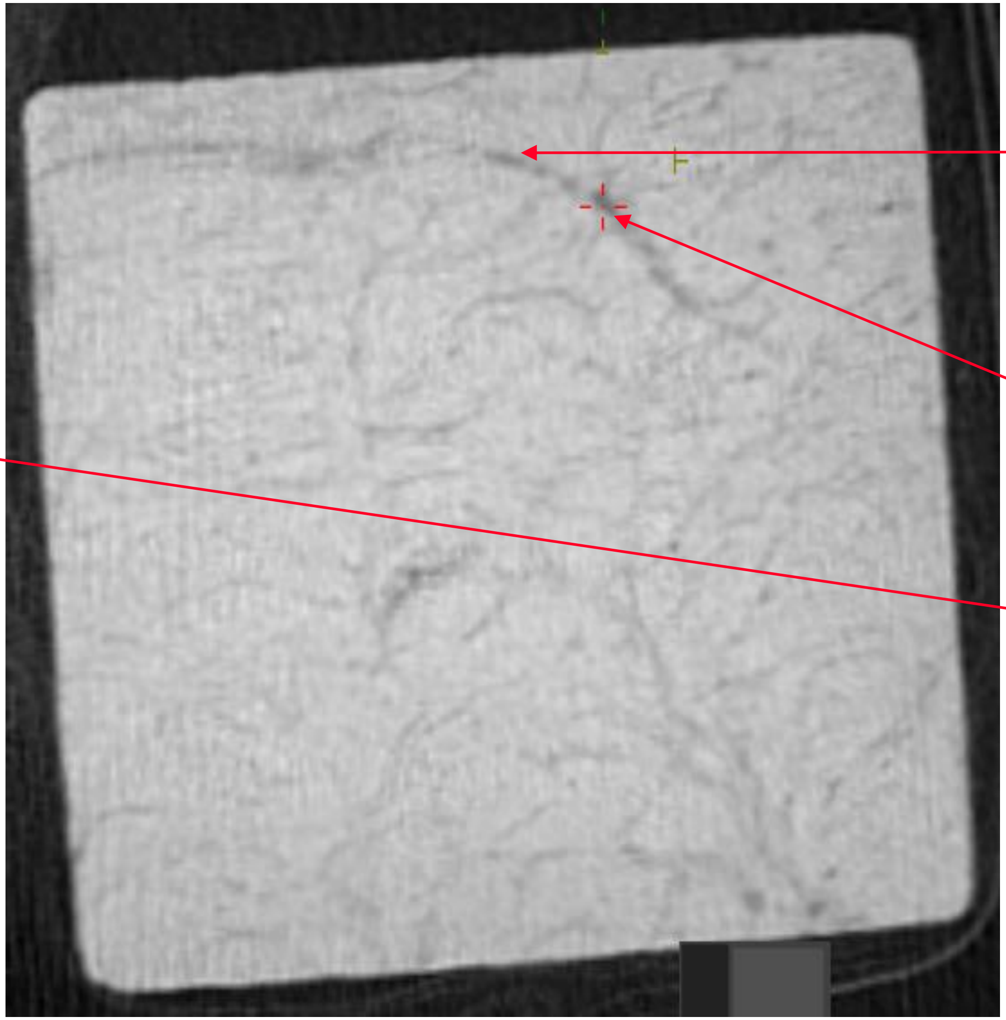
MA vs. CT: Fiber roving identified, but wrong defect detection





Fiber roving detected

A non-existent defect found

Real defects not identified

Podsumowanie

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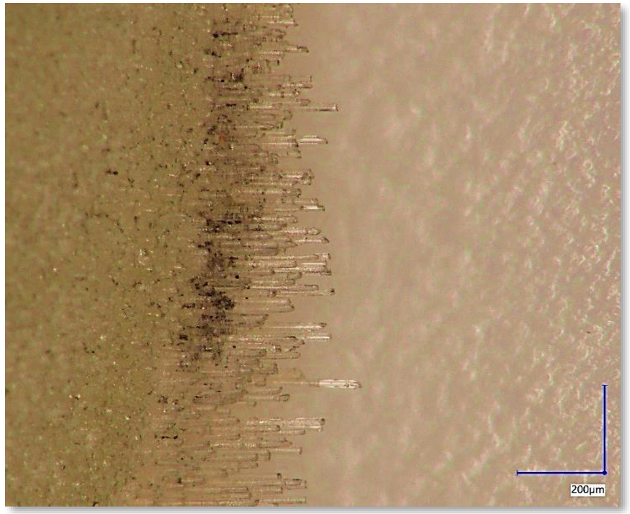
Wnioski końcowe:

- Drobne wady materiałowe są nieuchronnym elementem procesu produkcyjnego.
- Zaproponowa metoda zautomatyzowanego skanowania ultradźwiękowego (*water-immersed TFM*) pozwala skutecznie monitorować jakość produkcji kompozytowych elementów izolacyjnych WN.
- Skuteczność zaproponowanej technologii ultradźwiękowej jest porywnywalna do tomografii komputerowej, przy koszcie stanowiącym 10% kosztu referencyjnego.
- Analiza mikroskopowa (niszcząca) ujawniła, że rzeczywista jakość komponentów izolacyjnych jest znacznie lepsza niż zakładane limity jakościowe.



Uwagi ogólne:

- Te same pomysły (np. *beamforming*) są wykorzystywane w bardzo różnych segmentach przemysłu. Warto się rozglądać (zaczynać od aplikacji militarnych).
- Rozwiązanie programistyczna (np. *digital beamforming*) pozwala znacznie poprawić rozwiązanie sprzętowe (*physical beamforming*). Warto uzupełniać i łączyć.

Szczegóły techniczne prezentowanego rozwiązania:

➢ *Ultrasonic testing of glass fiber-reinforced polymer composites used in high voltage insulating components,* by Ziaja-Sujdak, Nowak, Ho, and Bobrowski
IEEE Transactions on Dielectrics and Electrical Insulation; 2024, 10.1109/TDEI.2024.3478132

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Co dalej?

- Kamera akustyczna CRY2624 / CRY8124
- Kamera montowana do drona CRY2626G

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Szczegóły techniczne rozwiązania

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Ultrasonic testing of glass fiber-reinforced polymer composites used in high voltage insulating components.

Aleksandra Ziaja-Sujdak, Tomasz Nowak, Chau Hon Ho and Pawel Bobrowski

***Abstract* — Due to their high strength-to-weight ratio and good dielectric properties fiber-reinforced polymers have gained significant interest in different industrial fields including the automotive, aerospace, and energy sectors. Despite this attention, the evaluation of the properties of polymer-based composite components, both as part of a post manufacturing quality assurance checks as well as for remaining service life estimation, remains challenging. In this paper, Ultrasonic Testing is investigated as a nondestructive approach for quality evaluation of High Voltage composite insulators. Classical Phase Array Ultrasonic Testing is compared with the Total Focusing Method. The results are validated using Computer Tomography and a destructive testing approach, which revealed microcracks and small voids.**

***Index Terms* — ultrasonic testing, fiber-reinforced composites, high voltage insulating components.**

I. INTRODUCTION

Due to the complexity of the production process of composite insulating materials, and in particular elements made of glass fiber-reinforced polymer composites, the formation of voids seems inevitable. Since these types of material defects can cause partial discharges (PD) and thus, in the longer run, affect the service life of high-voltage electrical equipment, it is important to monitor insulating elements for their material quality and proactively prevent potential PD problems, early in the according to their scale into *micro-voids* (formed in-between the fibers), *meso-voids* (in-between the tows), and *macro-voids* (larger zones, observable with the naked eye, not impregnated by macroscopic resin flow). Despite systematic analysis of void formation which began approximately 40 years ago (in 1980s), the details of the formation processes and all physical mechanisms are not yet fully understood. However, it can be shortly summarized that during the formation of *micro-* and *meso-voids* the resin viscous flow between the tows is driven by hydrodynamic forces, while between the fibers the capillary pressure (surface tension) becomes a dominant factor to drive the resin flow. Both effects can be quantified by a capillary number [2]. In addition, fiber volume fraction, macroscopic and tow permeabilities (as a function of saturation), flow direction, and geometrical anisotropy have been found to be important in void formation processes [2]. After voids are generated, they may be compressed by or dissolved (diffused) into the resin. Some initial voids disappear, others shrink or expand – depending on whether the resin is undersaturated or supersaturated with gas. Some voids, especially those between tows (*meso-voids*) can move easily with the resin flow, while micro-voids are more difficult to remove and often remain where they were formed. It must be therefore pointed out, that producing a fully defect-free composite element is problematic, highly (often too) expensive, and practically often not even necessary. A more pragmatic approach assumes that voids and other manufacturing defects can exist in the material, if they are

methods.

B. Experimental setup

To compare the capabilities of ultrasonic testing with physical and synthetic beamforming on a fiberglass reinforced composite material, the *pulse-echo* inspection configuration depicted in Fig. 3 was used to obtain PAUT and TFM images.

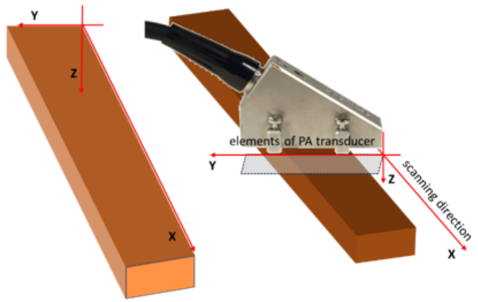

Fig. 3. Schematics of inspection configuration used for water immersion ultrasonic testing

A beamlike structure with rectangular cross-section was inspected using commercial Olympus OmniScan X3 Phase Array and TFM Flaw Detector. A standard commercial 2.25 MHz and 5 MHz Olympus Linear Phased Array Probe with 64 elements (38.4 x 10 mm Total Active Aperture, 0.60 mm Pitch) were used for PA and TFM respectively. The scanning process was fully automated, as schematically shown in Fig. 4. The measurement setup consisted of: 1 – flaw detector, 2 – transducer, 3 – tested object, 4 – supporting elements, 5 - moving platform, 6 – sliders, 7 – drive belt, 8 – stepper motor with encoder, 9 – water tank. The scanning process was realized with a resolution in the x-direction of 0.5 mm.

material was estimated to be 3500 m/s. Signal excitation and data acquisition was implemented in the OmniScan flaw detector. Additionally, the Time-Corrected Gain (TCG) flaw detector built-in function was used to reduce the effect of material damping on the detected signature. For TCG, three artificial defects (flat-bottom holes) with diameters of 1.2 mm were introduced by drilling (Fig. 5). The ultrasonic data, in the form of a three-dimensional matrix with *A-scan* envelopes from all focal points, were further post-processed using the Python programming language to obtain ultrasonic images and perform automatic quality assessment.

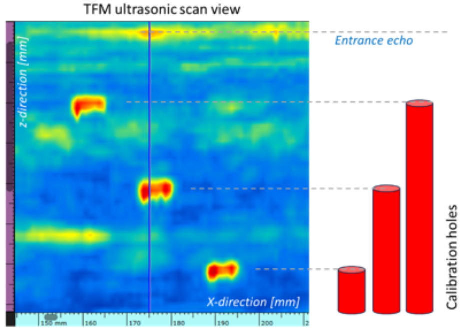

Fig. 5. TCG calibration with introduced flat-bottom holes ϕ1.2 mm as artificial defects. Colors in the ultrasonic view correspond to signal amplitude.

C. Ultrasonic images

Different ultrasonic images can be defined to help structural integrity assessment, with the most important ones being *C-scan*, *B-scan*, and *D-scan*. Following the nomenclature

IEEE Trans. Dielectrics and Electrical Insulation, February 2025, Vol. 25 No. 1, pages: 92-101

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