Application of NDT System for the Detection of Imperfections and Characterization of FSW Joints

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10th Meeting
SVETS Kommissionen
AG 52 FSW Processing

5th - 6th November 2013
University West
Trollhättan, Sweden

RTD Team for NDT of FSW

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- ☞ the **Helsinki University of Technology (TKK)**, founded 1849

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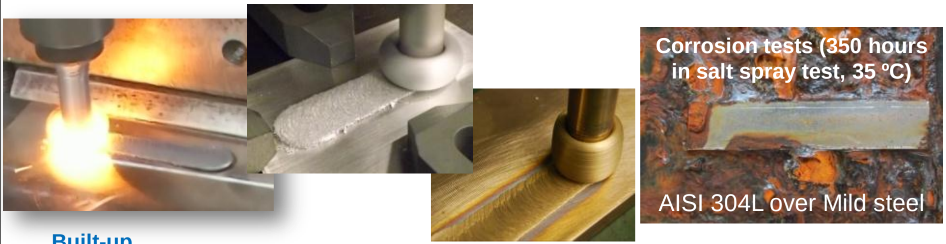
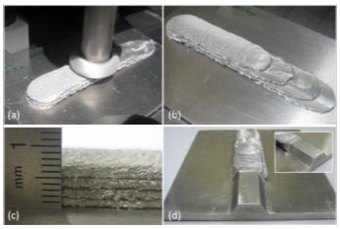
Materials Joining and NDT

R&D in FSW Allied Techniques

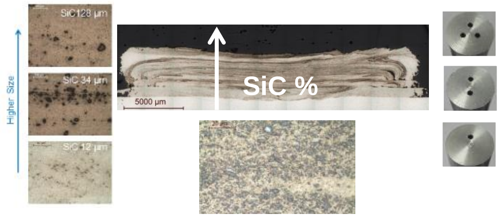
Friction Surfacing



Built-up
Rapid Prototyping

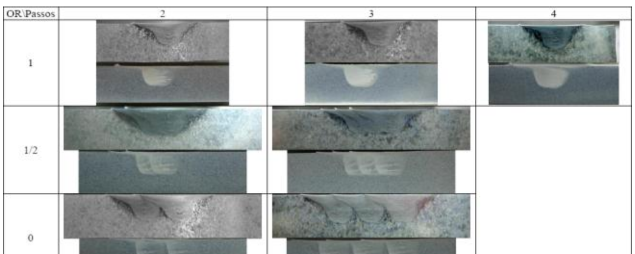


Production of Composites
Functionally Graded Materials

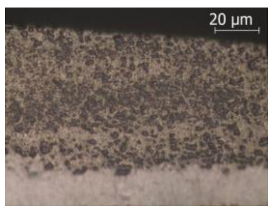


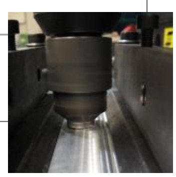
R&D in FSW Allied Techniques

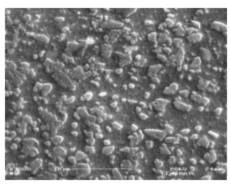
Friction Stir Processing



$$OR = 1 - \left[\frac{l}{d_{pino}} \right]$$

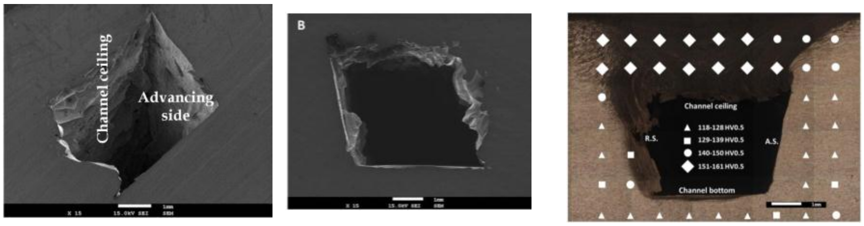




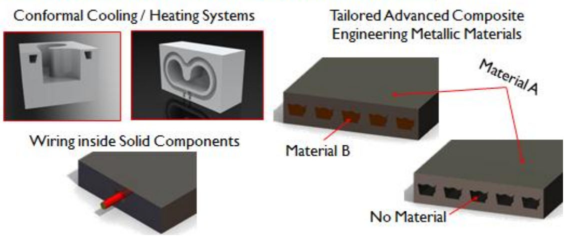


R&D in FSW Allied Techniques

Friction Stir Channeling



Potential Industrial Applications



Industrialization of FSW

…Demands Reliable Quality Assessment

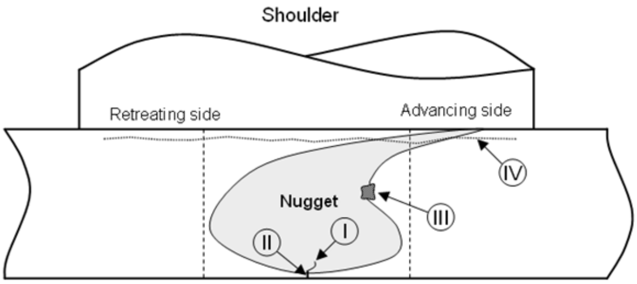
- The transference of FSW to high quality demanding industries depends on the level of reliability of the weld joins

- However the actual NDT reliability in characterizing and sizing the typical FSW defects still remains a challenge

- Thus the development of reliable NDT techniques is fundamental

Friction Stir Welding

Possible Defects – e.g. Butt Joints



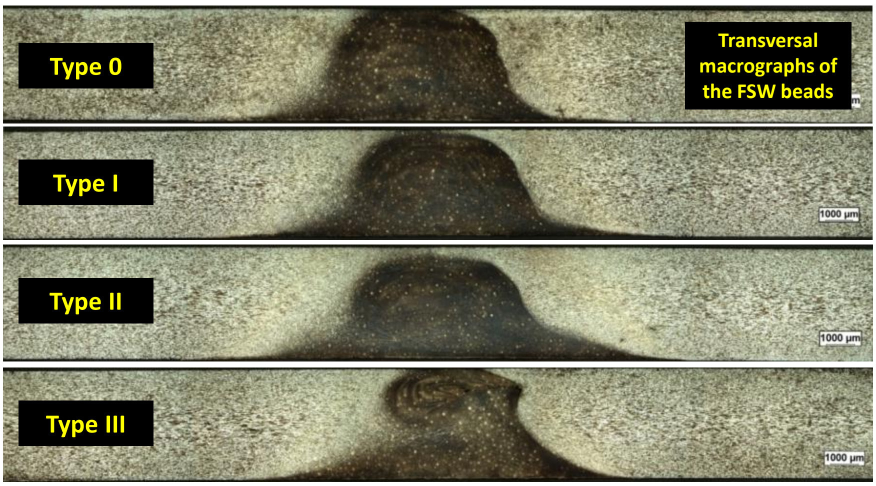
Types of defects:

I) Root flaw (weak or intermittent linking)
II) Lack of penetration (kissing-bond)
III) Internal voids (material flow boundaries with lack of forging pressure)
IV) Particles alignment under shoulder (second phase particles and oxides)

Friction Stir Welding

Defects – Size, Location, Morphology

Production and characterization of the typical defects of FSW

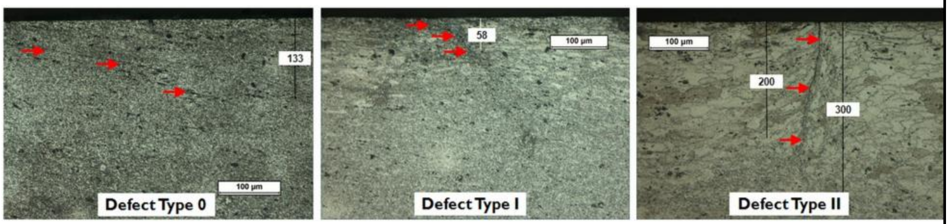


Friction Stir Welding

FSW Parameters for Defects Type

AA2024-T351 plates ; thickness = 3.8 mm

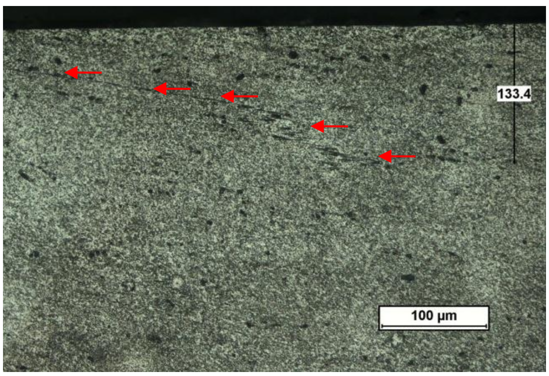
Defect Type	V (mm/min)	Ω (rev/min)	L_{pin} (mm)	F_Z (kg)
0	224	710	3.8	950
I			3.6	
II			3.3	



Friction Stir Welding

Defects – Size, Location, Morphology

Type 0

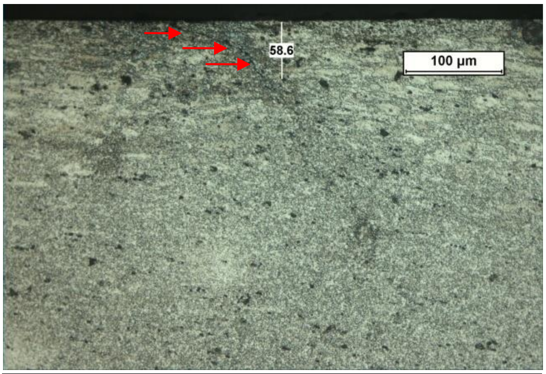


- Particles alignment ~ 100 µm
- Location : Superficial defects at the root of weld bead

Friction Stir Welding

Defects – Size, Location, Morphology

Type I



- Lack Of Penetration ~ 60 µm + particles alignment
- Size: Very small (typically: 20 µm < ℓ <300 µm)

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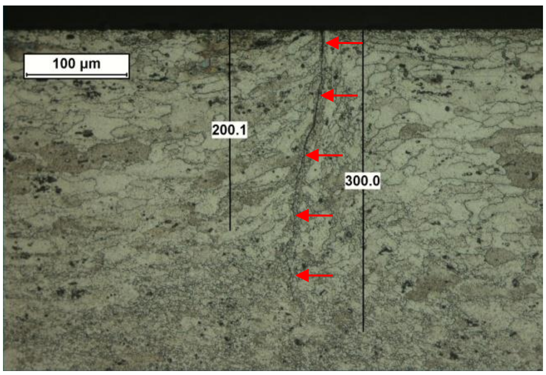
Materials Joining and NDT

Friction Stir Welding

Defects – Size, Location, Morphology

Type II



- Kissing-Bond ~ 200 µm + particles alignment
- Morphology:
  - No physical discontinuity
  - Weak effect of energy changes (EC, UT, RT)
  - Change of the material properties even without defects

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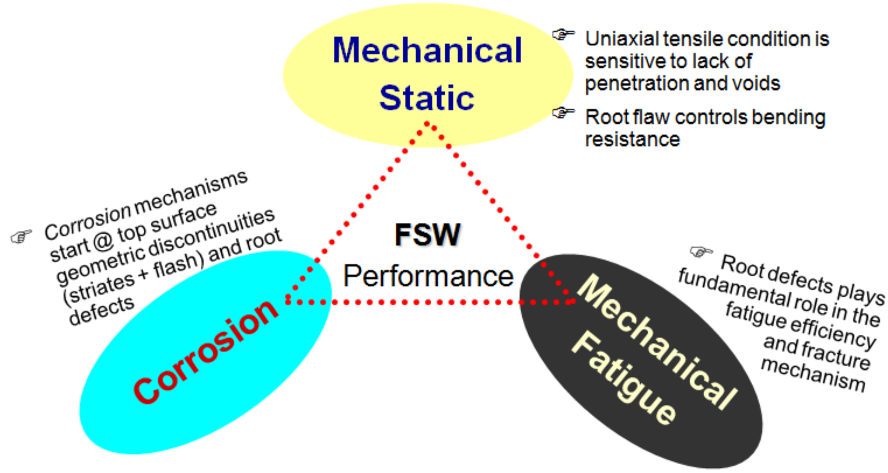
Materials Joining and NDT

Friction Stir Welding

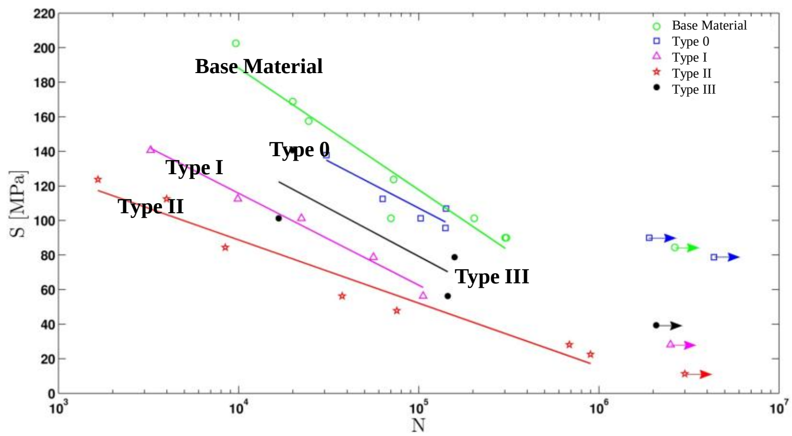
Effect of Defects



Friction Stir Welding

Effect of Defects

S-N diagram for the fatigue behavior

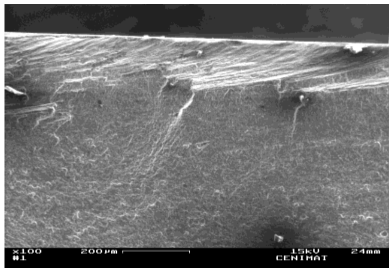


The most significant defects are the roots ones. Thus, **root defects are the target defects on the NDT** Techniques

Friction Stir Welding

Defects – Size, Location, Morphology

☞ e.g. ***Root Flaws:***
(weak or intermittent link)

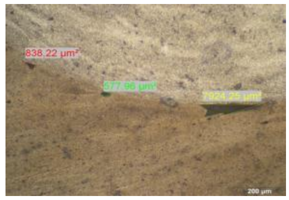


Size:

-Very small (typically: 20 µm < ℓ <500 µm)

Location:

-Superficial (defects at root and shoulder contacting surface) ➔ Difficult with ultra-sounds
-In-volume ➔ Difficult with eddy current

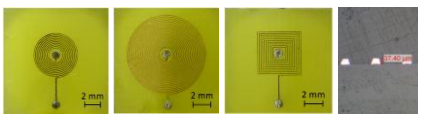


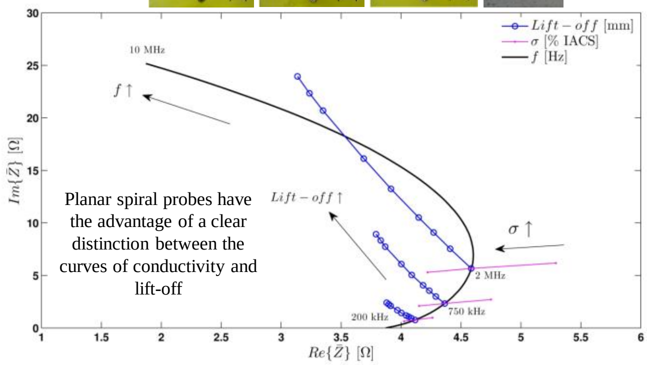
Morphology:

-No physical discontinuity (even in lack of penetration)
-Weak effect of energy changes
-Change of the material properties even without defects

NDT for FSW

Conventional Eddy Current Probes

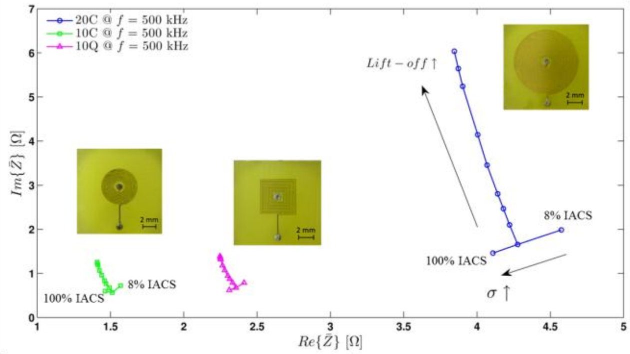




NDT for FSW

Conventional Eddy Current Probes

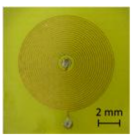
However this type of probes are high sensitive to the lift-off changes. In fact, the planar spiral coils show a very low sensibility to the conductivity changes, even in extreme conditions (from 100% IACS to 8% IACS)

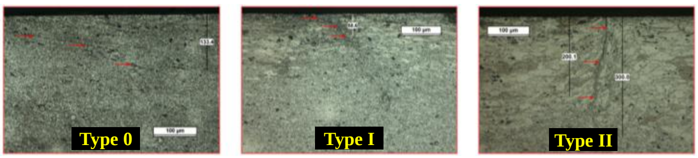


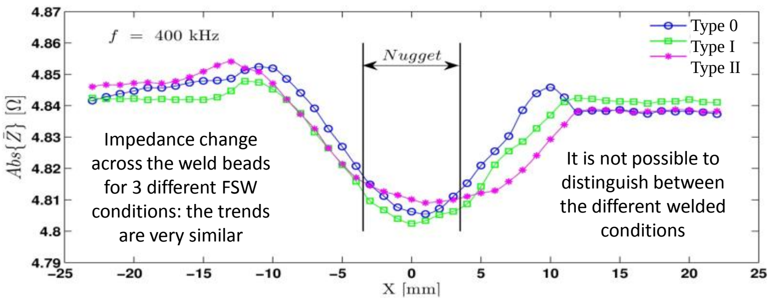
NDT for FSW

Conventional Eddy Current Probes

Planar spiral probes have no sensitivity to FSW root defects



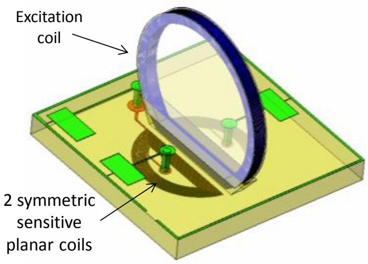


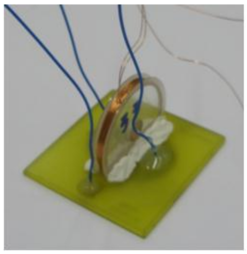


Innovation in Eddy Current Probes

IOnic Probe

New concept of eddy current probe dedicated for FSW was developed:





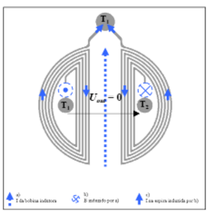
2008 Patent

- **Characterized by a symmetric sensitive coil perpendicular to the inductor coil**
- **Less sensitive to the lift-off effect**
- **More sensitive to micro FSW defect**

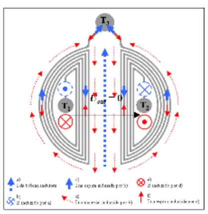
IOnic Probe

Principle of Operation

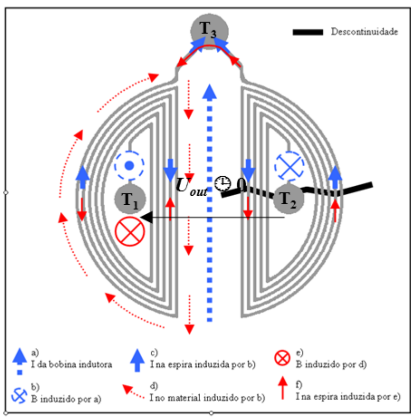
On the air

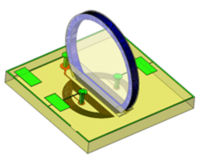


Under a base material



Under a defect

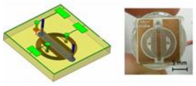


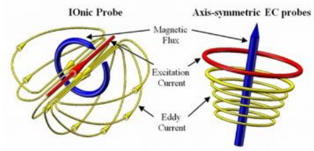


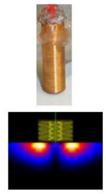
When a defect emerge under one halve of the sensitive coil there is an imbalance of the eddy currents, producing a impedance change

IOnic Probe
Operating Characteristics

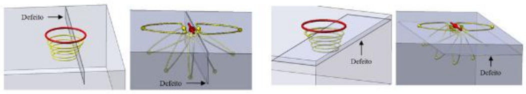
- 3D induced eddy current in the material



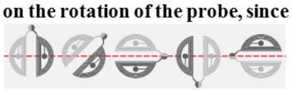




- A great change of the eddy currents duo to the defects, allowing the detection of defects parallels to the surface



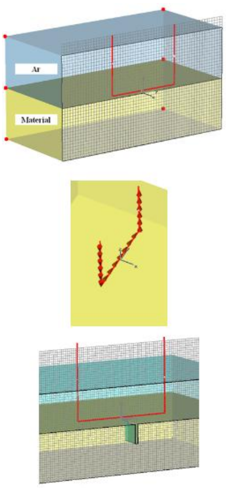
- Method of inspection based on the rotation of the probe, since it is not axis-symmetric



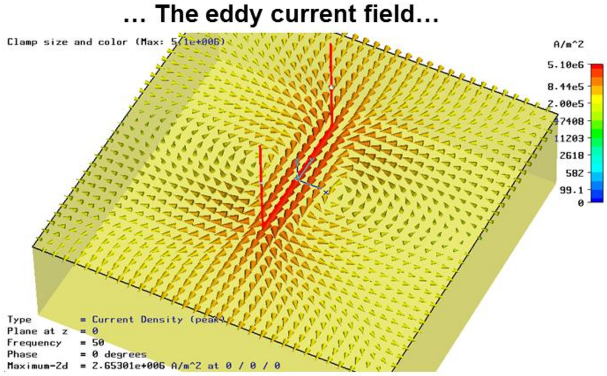
- The straight direction of the eddy currents can be useful if there is a heuristic concerning to the orientation of the defects

IOnic Probe
Numerical Simulation

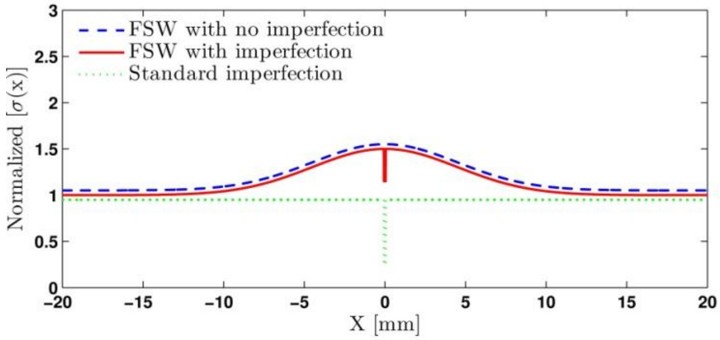
Results from FEM software CST EM Studio



… The eddy current field…

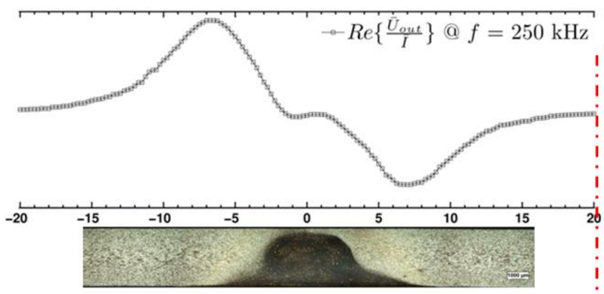


Conductivity Across FSW Bead
Analytical Modeling

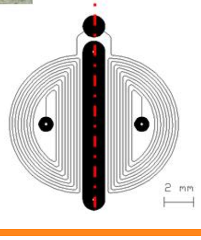


It is necessary distinguish booth electric conductivity changes: defects and sound welds

NDT Application to FSW
IOnic Probe Results

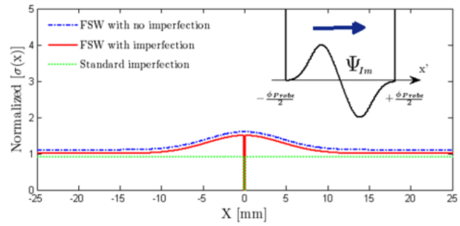


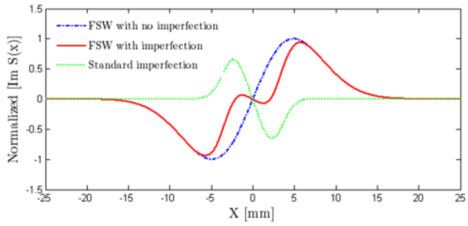
The IOnic Probe was moved across the weld beads…



NDT Application to FSW

IOnic Probe Signal





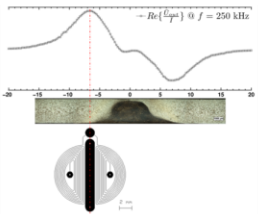
How can we understand this results?...

We can imagine the IOnic probe as a mathematical function: $\Psi_{probe}(x')$.

The experimental signal S(x) is the product between $\Psi_{probe}(x')$ and the electric conductivity field $\sigma(x)$.

Moving this mathematical product across the weld beads we obtain the complete signal S(x).

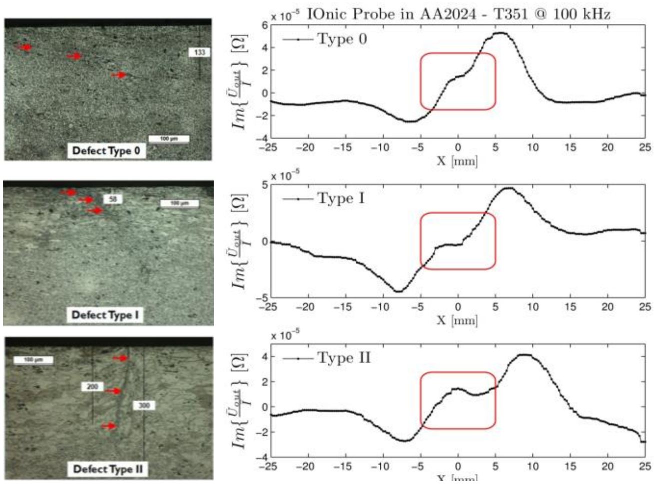
$$S(x) = \int_{x-\frac{\phi_{Probe}}{2}}^{x+\frac{\phi_{Probe}}{2}} \sigma(u) \cdot \Psi_{Probe}(x')\, du$$

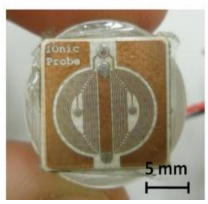


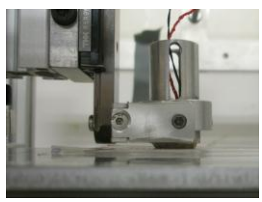
NDT Application to FSW

IOnic Probe Results

The results clearly show a signal disturbance which is proportional to the size of the defects



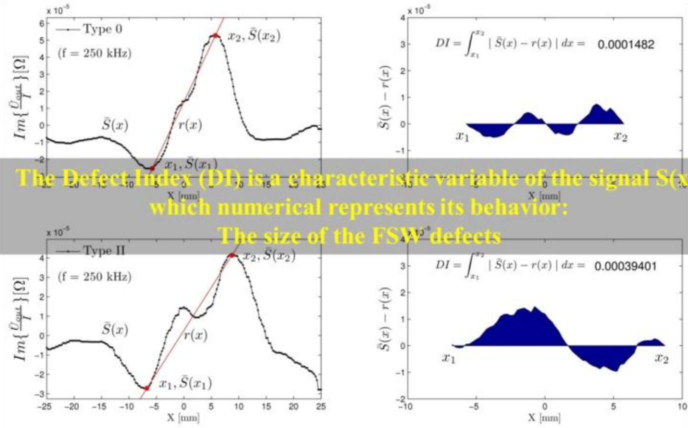




NDT Application to FSW

Defect Index

- ✓ Dedicated algorithm was computational implemented to quantify signal disturbance, allowing defects sizing
- ✓ The algorithm compute the area defined by the difference between the signal S(s) and the line r(x)

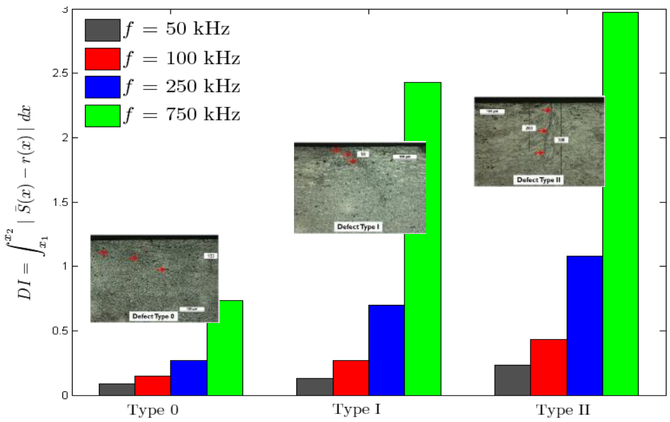


The Defect Index (DI) is a characteristic variable of the signal S(x), which numerical represents its behavior: The size of the FSW defects

NDT Application to FSW

Defect Index

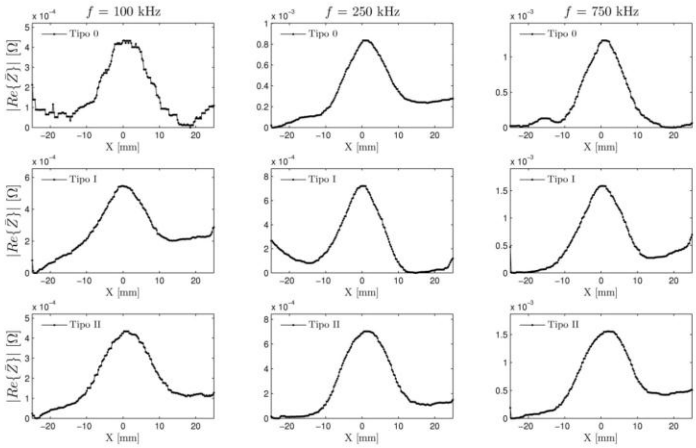
The application of the Defect Index to the 3 defects types clearly show a proportionality between then. This result is confirmed by different frequencies.



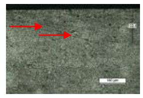
NDT Application to FSW

Circular Spiral Planar Probe

When using the planar spiral probes, the 3 curves present a very similar trend between them. In fact, unlike the IOnic probe there is no distinctive signal feature allowing the distinguish between each defect condition

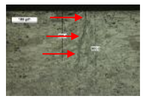


Particles



~ 60 µm

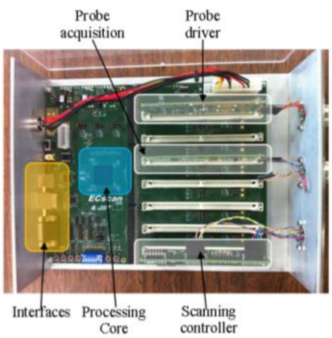
~ 200 µm



Innovation in Eddy Current Probes

New features of IOnic Probe (1/5)

Prototype of the dedicated NDT electronic system for IOnic Probes



- ✓ Generate + Analyze the probe signals using digital processing
- ✓ Allows controlling scanning devices with up to three axis
- ✓ The use of programmable digital logic devices and the possibility to configure the number and type of peripherals on the probe interface enables the system to be reconfigured in agreement with probe and testing requirements
- ✓ Several communication interfaces allow the system to be controlled using a PC

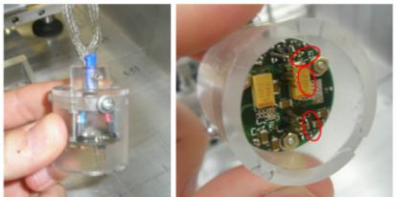
Innovation in Eddy Current Probes

New features of IOnic Probe (2/5)

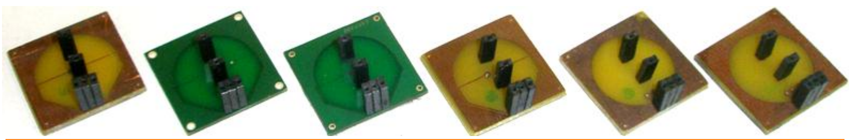
New system uses a customized support where the IOnic Probes are fixed and connected.

✓ This support also includes an electronic pre-amplifier allowing to measure very small amplitude signals without the influence of cables electromagnetic noise added.

Universal IOnic Probe support:



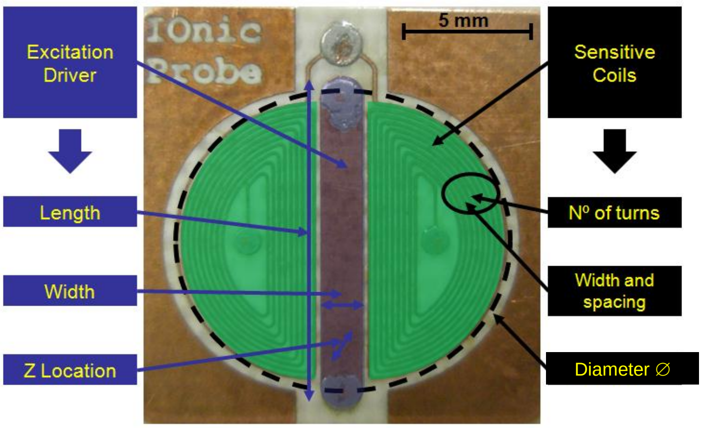
IOnic Probe connections:



Innovation in Eddy Current Probes

New features of IOnic Probe (3/5)

Optimization of IOnic Probe: 6 main geometric parameters

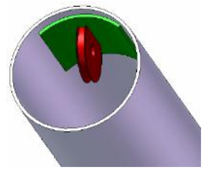


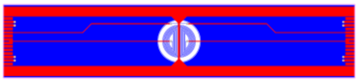
Innovation in Eddy Current Probes

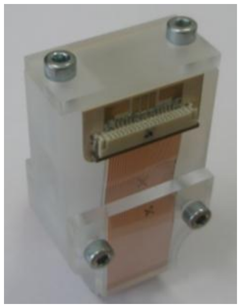
New features of IOnic Probe (4/5)

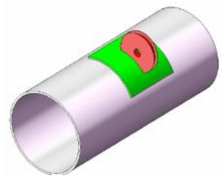
Production of Ionic Probe on flexible subtracts (e.g. Kapton®)

☞ Allow NDT Inspection of curved surfaces







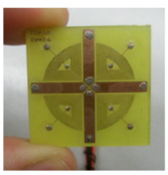


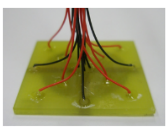
Innovation in Eddy Current Probes

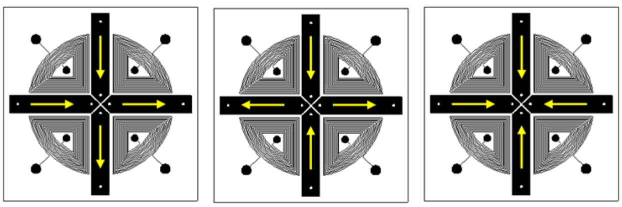
New features: The IOnic Probe Plus (5/5)

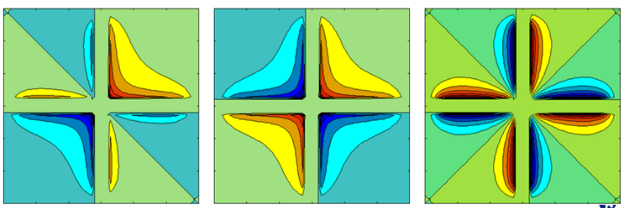
- **Allow different electronic configurations depending of the excitation mode**

PT N.º 104089







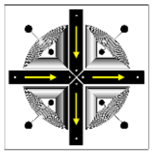


Magnetic fields associated to the different excitation modes

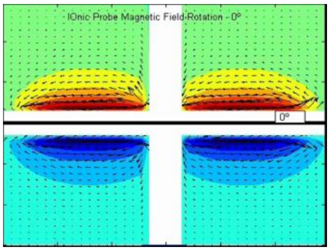
Innovation in Eddy Current Probes

New features: The IOnic Probe Plus (5/5)

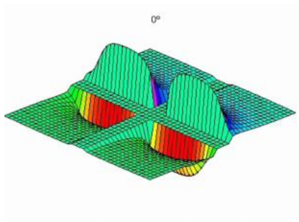
The main advantage of the IOnic Probe Plus is the electronic rotation of the direction of the magnetic field :



by changing the amplitude and/or phase of the current in the excitation filaments



- Complete signal analysis along one rotation
- Detection of defects parallel to the surface
- Complete NDT Inspection of all the geometry including the components edges



… Allowing the detection of defects in all directions, and a very "rich" data acquisition

Conclusions

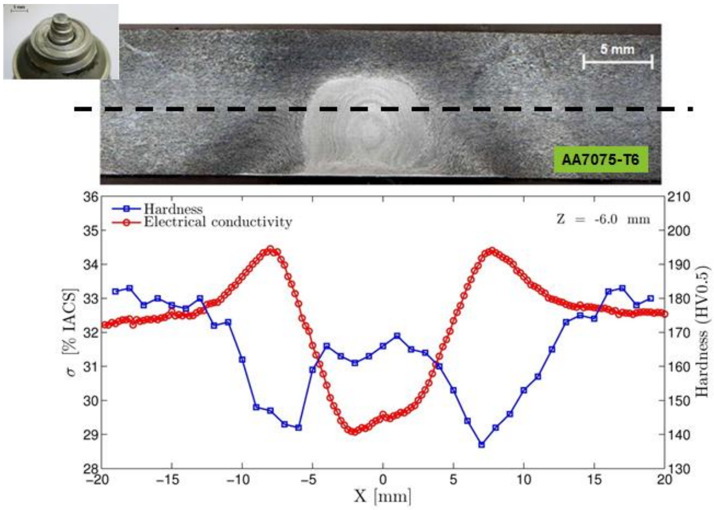
IOnic Probe Application to FSW

- Conventional axis-symmetry EC probes such as planar circular spiral probes are not able to distinguish small local variations of conductivity, caused by typical FSW root imperfections with depth below 200 µm

- The experimental results shown that the IOnic Probe is able to identify different levels of FSW root defects by a distinctive perturbation on the output signal. It was also shown that exist a good proportionality between the defects size and this signal perturbation

New Application of Eddy Currents

Evaluation of Structural Properties (1/5)



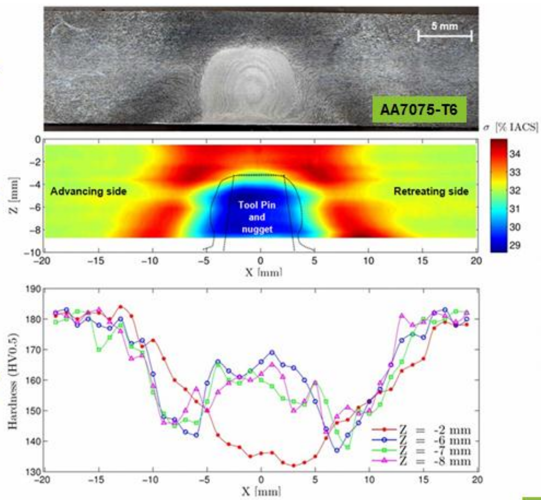
New Application of Eddy Currents

Evaluation of Structural Properties (2/5)

Macro

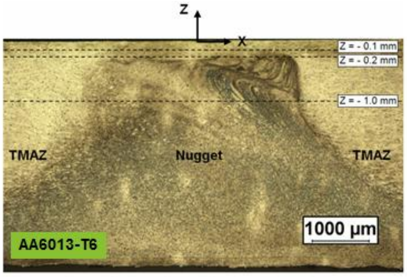
Electric Conductivity

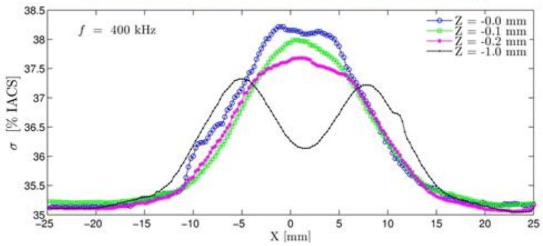
Hardness



New Application of Eddy Currents

Evaluation of Structural Properties (3/5)



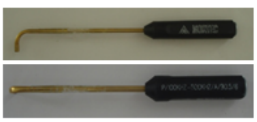


New Application of Eddy Currents

Evaluation of Structural Properties (4/5)

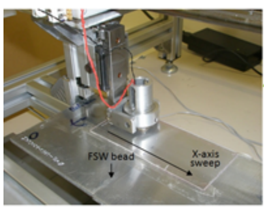
Experimental Procedure

The electrical conductivity measurements:



Absolute helicoidally shielded eddy current (EC) probe

Permanent lift-off of thin polymer of 50 µm thickness.



Conductivity measurements were made along a sweep in the X-axis perpendicular to the processed bead, at half thickness.
90 mm long segments were characterized with 200 µm distance between each value acquisition.

Measurements were taken in samples extracted from the starting and ending zones of the processed runs.

Microhardness Vickers measurements:
Load = 1.96 N (HV02)

New Application of Eddy Currents

Evaluation of Structural Properties (5/5)

	Hardness	Electric Conductivity
Observed Area	•	●
Basic Phenomena	**"Macro"** (Dislocations and Precipitates)	**"Micro"** (Electronic Mobility)

T. G. Santos, R. M. Miranda, P. Vilaça, J. P. Teixeira, *Electrical Conductivity Changes in Friction Stir Processed Aluminium Alloys*, Int. J. Advanced Materials Technology, 2011

T. G. Santos, P. Vilaça, R. M. Miranda, *Electrical conductivity field analysis of for evaluation of FSW joints in AA6013 and AA7075 alloys*, J. Mat. Processing Technology, 2011

Conclusions

Application of Eddy Currents to Evaluate Structural Properties

☞Measuring electrical conductivity field with eddy current probes shows potential to constitute a feasible, reliable and expedite procedure to pattern microstructural small scale features and is also able to detect superficial defects/discontinuities

☞Electrical conductivity is controlled by local electronic mobility and thus is very sensitive to local grain size and less sensitive to precipitation and dislocations

☞For FSW of heat treatable aluminium alloys the electrical conductivity typically decreases in the nugget and increases in the TMAZ and HAZ. This evolution has typically an inverse consistence relation with hardness