An evaluation of new optical technologies for real-time laser weld monitoring

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Outline of the presentation

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- ❑ *Monitoring equipment*
- ❑ *Material and Laser Equipment*
- ❑ *Experimental Approach*
- ❑ *Results – IDM Sensor*
- ❑ *Laser Process Monitoring*
- ❑ *Results – Photodiode Sensor*
- ❑ *Summary and Conclusions*

Introduction

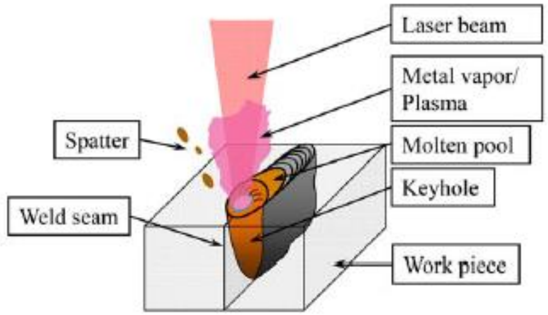
Laser welding

- one of the important technologies used in the **manufacturing of automotive bodies**
- **automotive manufacturers** are **replacing spot welding methods with laser welding** due to its high speed, non-contact and precision with low heat effects

primary concern for companies:
weld defects detection

Motivation

- ❑ Safe detection of critical errors
- ❑ Avoidance of production losses
- ❑ Automated inspection of all parts
- ❑ Provide feedback for process control
- ❑ Minimization of the cycle time



Schematic diagram of keyhole model laser welding

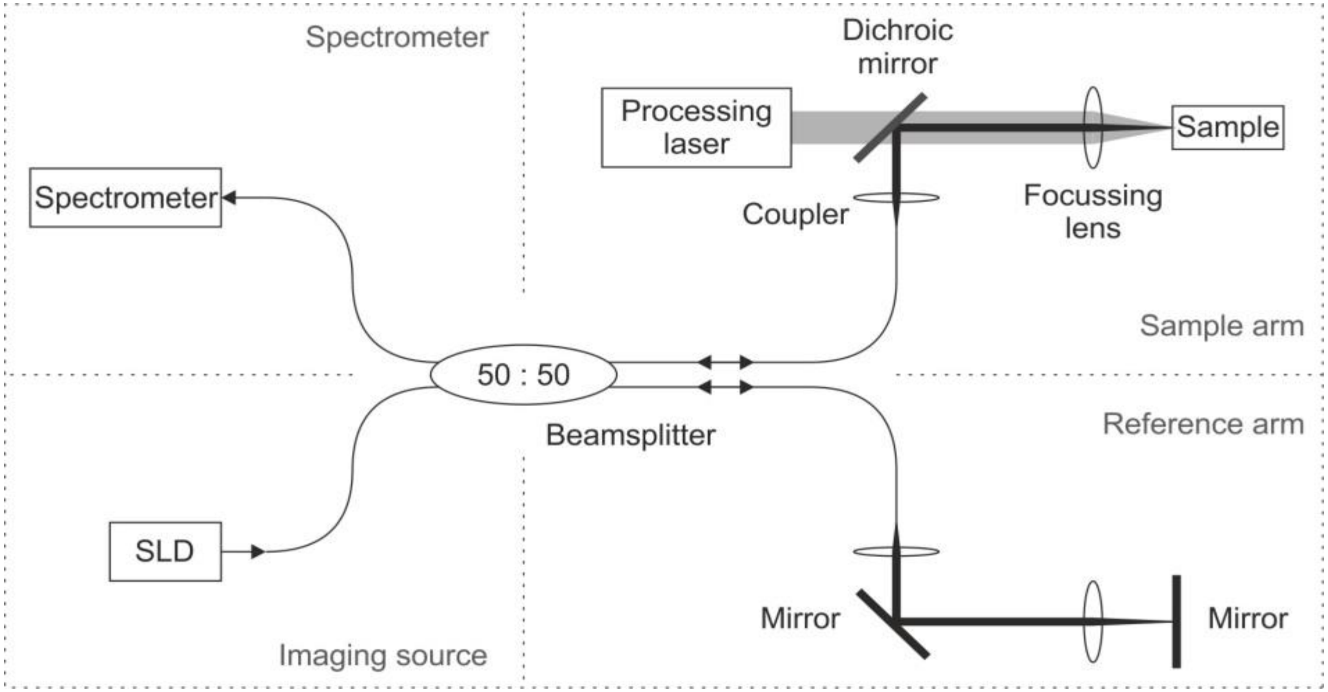
The laser-material interaction that occur during laser welding **emits energy in a variety of forms**

different on-line inspection systems have being developed

Monitoring equipment

1st approach - **Low coherence interferometry monitoring measuring variations in keyhole depth during welding**

1. Precitec In-process Depth Meter (IDM) system
2. Laser Depth Dynamics (LDD) system

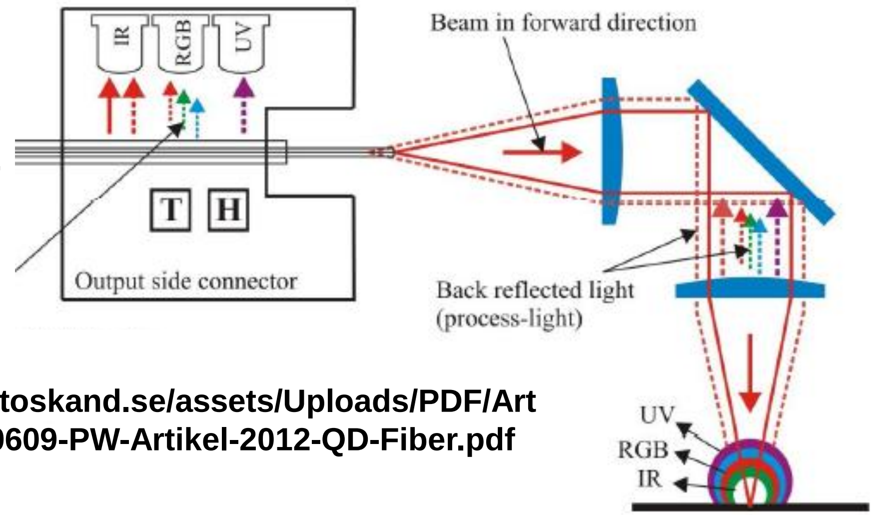


Working principle of Inline Coherent Interferometry. (Webster et al, 2014).

Monitoring equipment

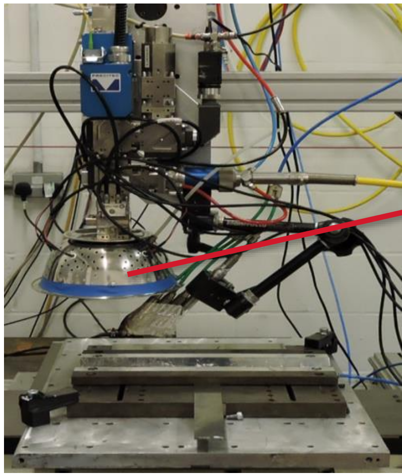
2nd approach - **Photodiodes**

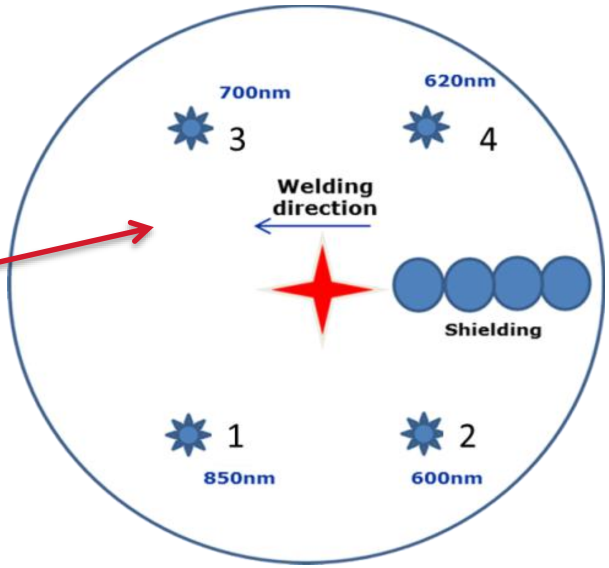
In-fibre built



www.optoskand.se/assets/Uploads/PDF/Artiklar/150609-PW-Artikel-2012-QD-Fiber.pdf

free standing





Material and Laser Equipment

Material	Thickness (mm)	Joint Configuration	Optical Sensor	Pre-welding preparation
Nickel (Ni) alloy 718	2.1 and 3.6	Butt and Bead-on-Plate (BoP)	IDM and Photodiode	• Abraded and acetone degreased • Dry machined square edges
DC01 mild steel	1.2	Lap	IDM	Acetone degreased
S355 Medium strength structural steel	6	Butt	Photodiode	Disc grinded and acetone degreased

Laser system

Laser	Multi-kW fibre laser
Wavelength	1070µm
Operation Mode	Continuous-wave
BPP, mm.mrad	~6
Fibre Diameter [µm]	150, 200
Collimating lens [mm]	160, 100
Focussing lens [mm]	160, 250
Spot size [µm]	200 or 300

Ranges of the parameters used in laser trials

Material	Speed (m/min)	Power (kW)	Focus (mm)
Ni 718	1.5-3	1 - 4	+6 to -16
DC01	3 - 4	1 – 5	-2
S355	1.5-3.0	5.0-7.5	+4 to -16

Experimental Approach

- Welding trials were carried out to generate process emissions
- Analysis of signals generated by two optical-based sensors:
  - Photodiodes responsive to either visible or near-infrared (NIR) emissions
  - In-process Depth Meter (IDM) sensor from Precitec
- Correlation with different types of weld features, imperfections and/or process anomalies

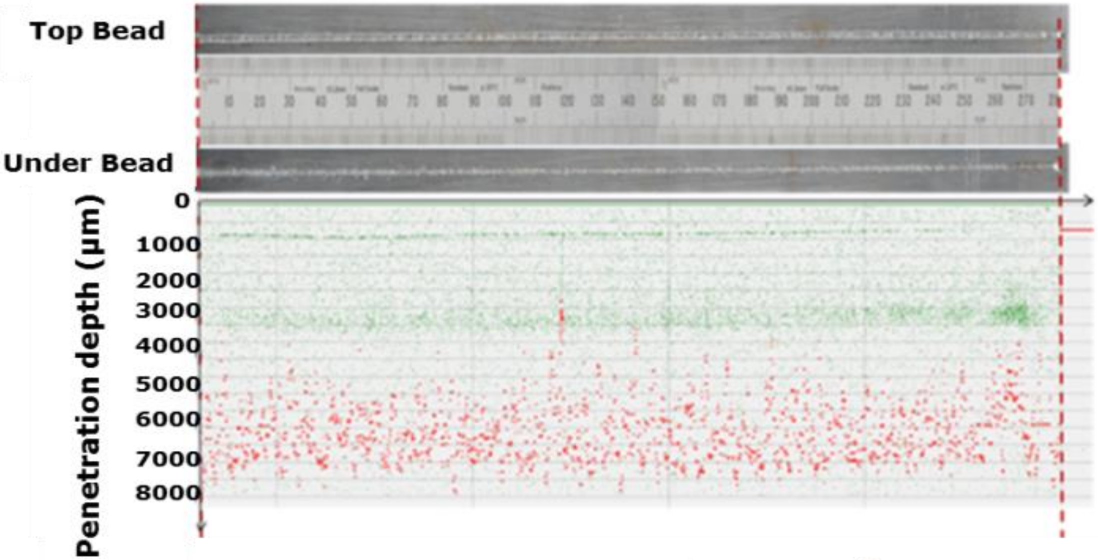
- Welds with known defects were produced by making the following changes:
  - Laser beam power
  - Cleanliness along the joint interface
  - Changes in joint gap
  - Changes in the laser beam alignment position with respect to the joint line

✓ **IDM: correlation between signal data and keyhole depth variations**

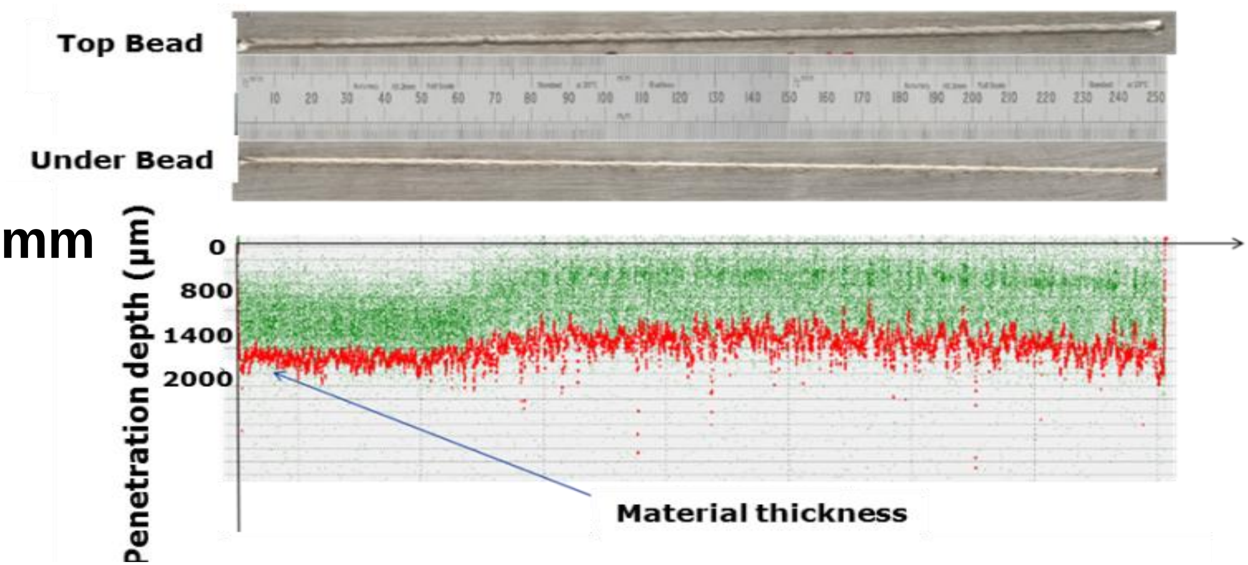
✓ **Photodiodes: signals correlated with different types of weld discontinuities, such as incomplete penetration, lost of power, internal porosity and beam to joint alignment**

Results – IDM Sensor

Fully penetrated welds



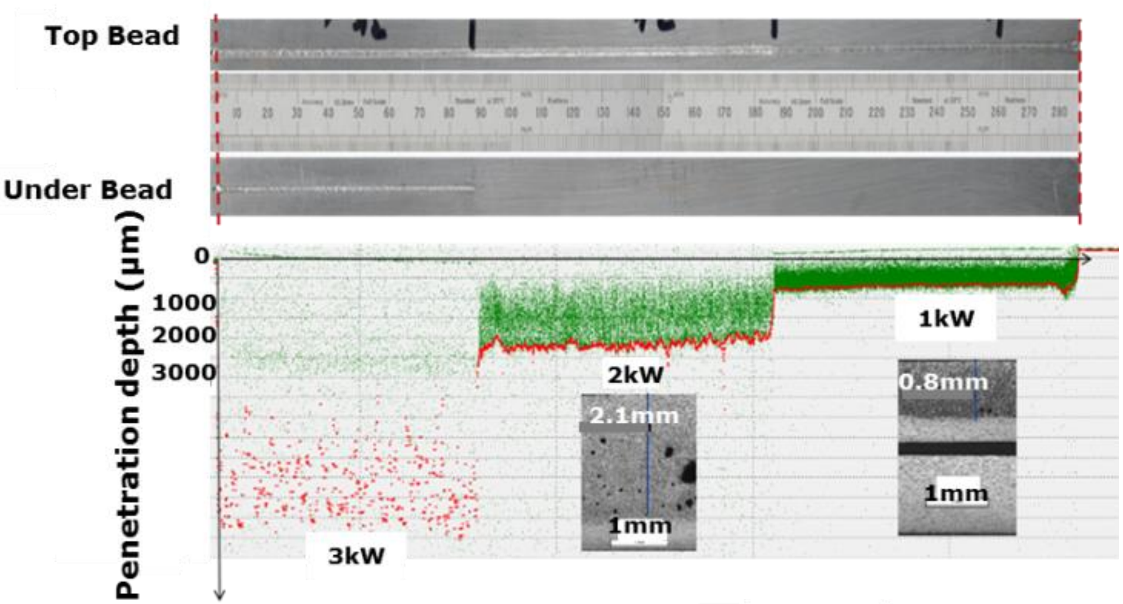
Full penetration in stake-welded DC01, total t=2.4mm



BoP in Ni 718 , total t=2.1mm

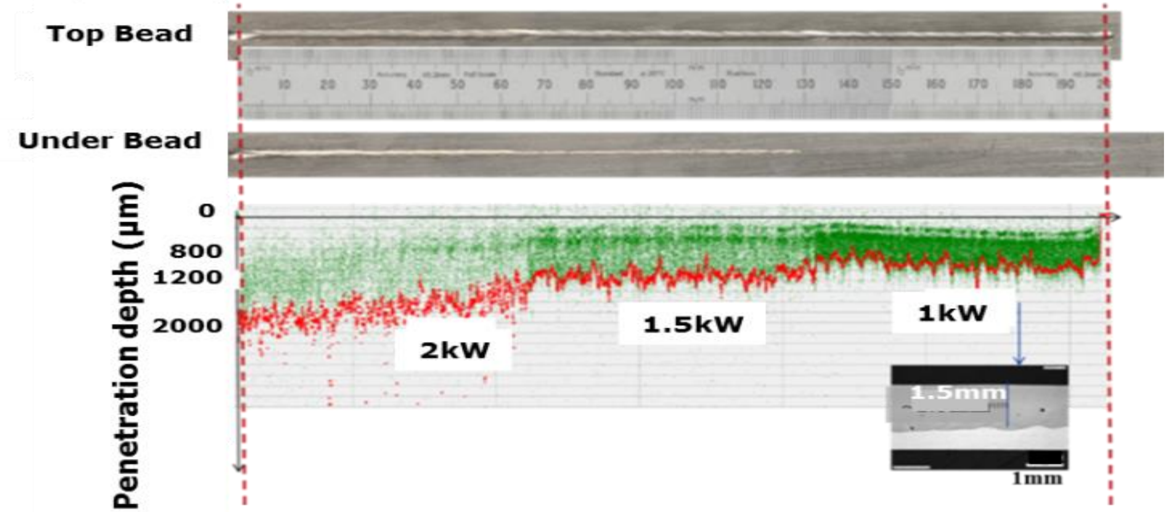
Results – IDM Sensor

Partial to full penetration depth due to power variation



Stake-welded DC01

BoP in Ni 718



Laser Process Monitoring

Investigation of an established optical monitoring method, using **photodiodes in the visible and infrared (IR) ranges**, to correlate the produced monitoring signals with different types of weld features, imperfections and/or process anomalies.

- ***occurrences of internal porosities***
- changes in penetration depth & beam to joint alignment
- changes in laser power & poor joint preparation
- cleanliness or fit-up

Advanced signal analysis methodology

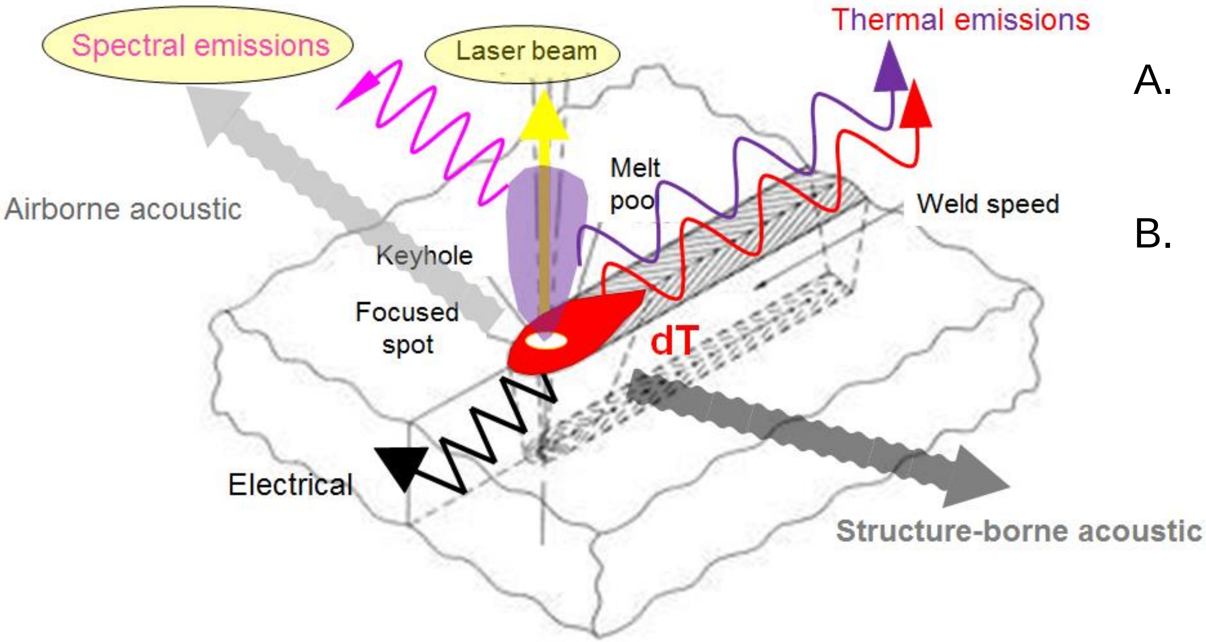
→ ***Singular Spectral Analysis (SSA)***

→ ***Orthogonal Empirical Mode Decomposition (OEMD)***

- **Fast**
- **Accurate**
- **No reference**

Photodiodes - Selection of detectable emissions

Process signals during laser welding



A. It is high desirable to diagnose laser process quality using these emissions
B. Understanding the relationship between emission characteristics and weld quality characteristics

Acoustic emission (AE) involves a **sensor which converts process sounds into electrical output to a measurable variable**.

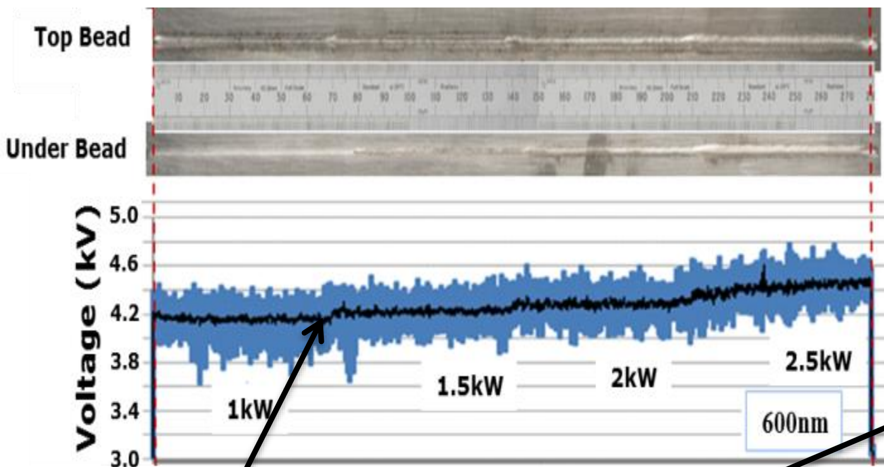
- **Air-borne emission has the human audible of ranges between 20Hz and 20kHz.**
- **The frequency of structure-borne emission is usual from 50kHz to 200kHz.**

Optical detector, particularly **ultraviolet (UV), visible or infrared (IR) detectors, has used to convert the flux density of the radiation emitted by the welding process into an electrical signal.**

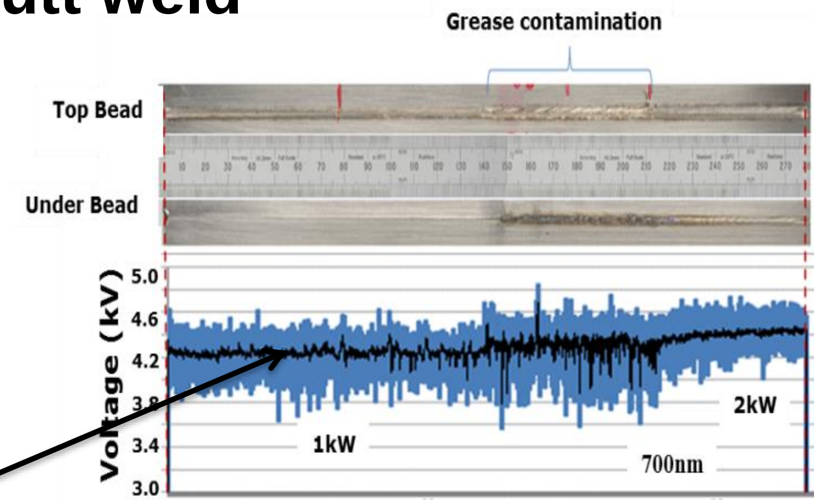
Optical filter is often **placed in front of the detector to confine the spectral ranges of the whole sensor system.**

Laser Process Monitoring – photodiode sensor

Ni 718 – Butt weld

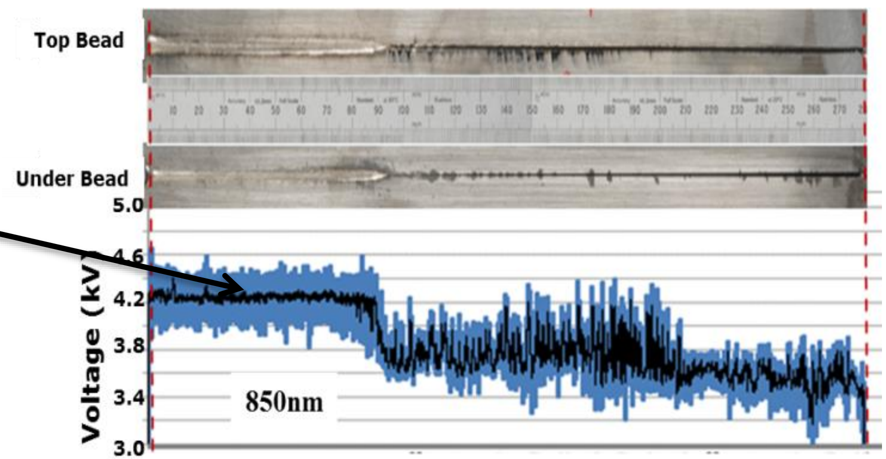


Power change



Grease contamination

Black line shows a running average of the raw data points

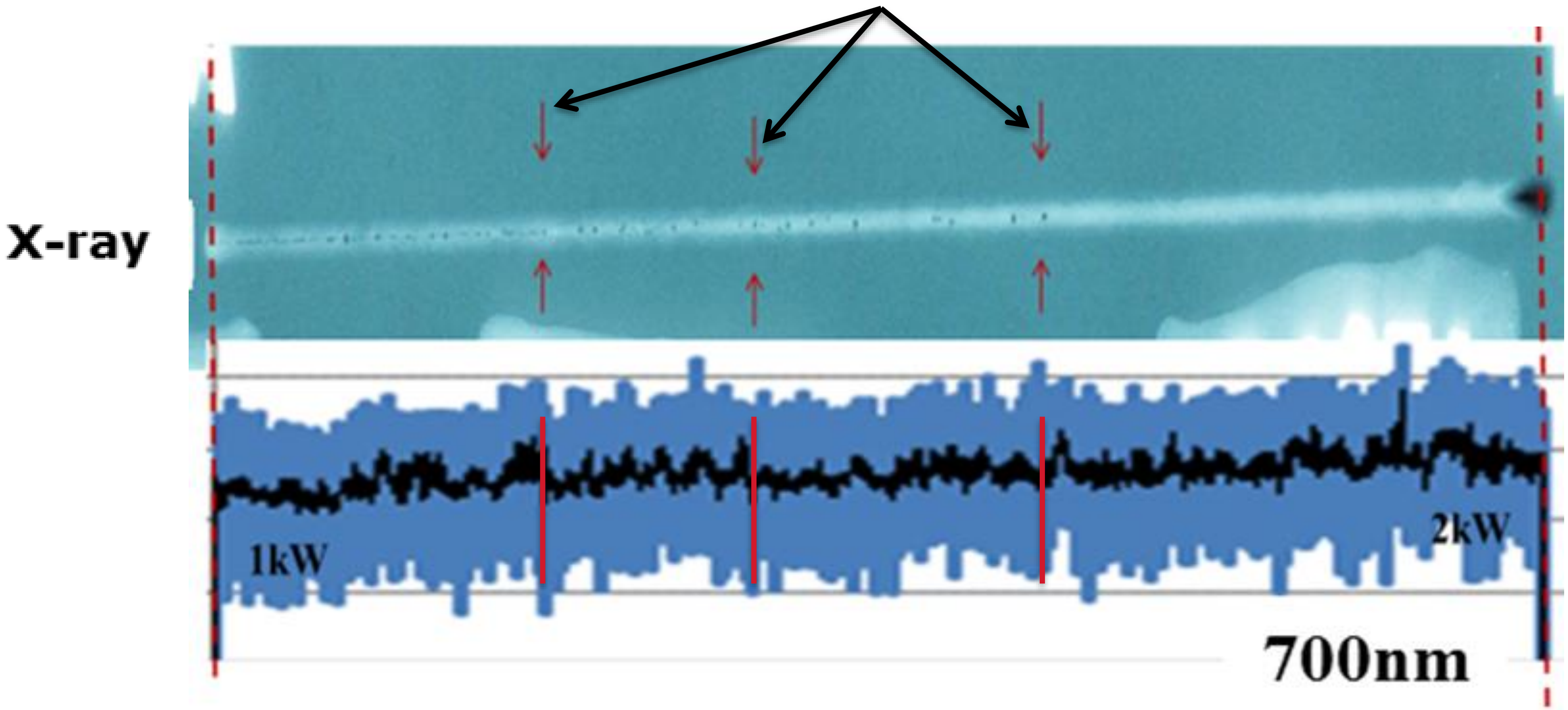


Welding over a gradually opening joint gap

Laser Process Monitoring – photodiode sensor

Ni 718 – BoP; Internal porosity

the arrows indicate **some locations where peaks in the signal data appeared to be in the proximity of the pores**



laser power ramped up from 1 to 2kW as welding proceeded, **to increase the level of penetration and correspondingly decrease the internal porosity content**

Laser Process Monitoring – photodiode sensor

Comparing the photodiode raw signal data and the X-ray radiograph

↓

it did not appear possible to establish any strong correlation between these signal peaks and individual pores detected within the radiograph

↓

1. the optical signals detected during the laser welding are typically **contaminated by different kind of noises that affect the photodetector**.
2. it is necessary to smooth and de-noise the signal for getting a "clean" signal.
3. the traditional method to de-noise process signals is to use digital **Butterworth filters**. Nonetheless, more advanced filtering techniques such as **discrete wavelet transforms, Wiener filtering** have also been used to that end. Although these methods have proven useful, their **main drawback is the complexity of devising an automatic and systematic procedure**

↓

Advanced signal analysis methodology

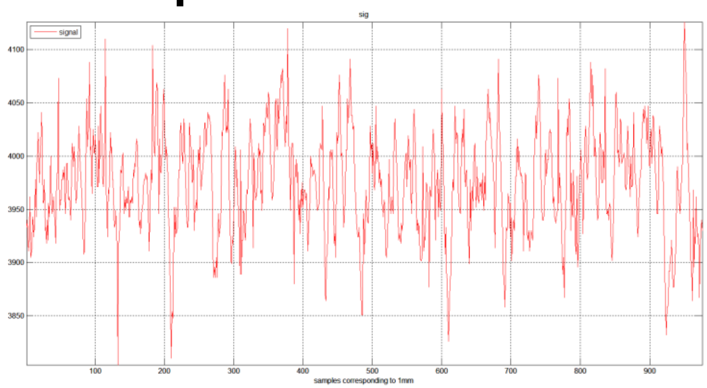
- ***Modified Singular Spectral Analysis (MSSA)***
- ***Orthogonal Empirical Mode Decomposition (OEMD)***

Laser Process Monitoring – signal analysis

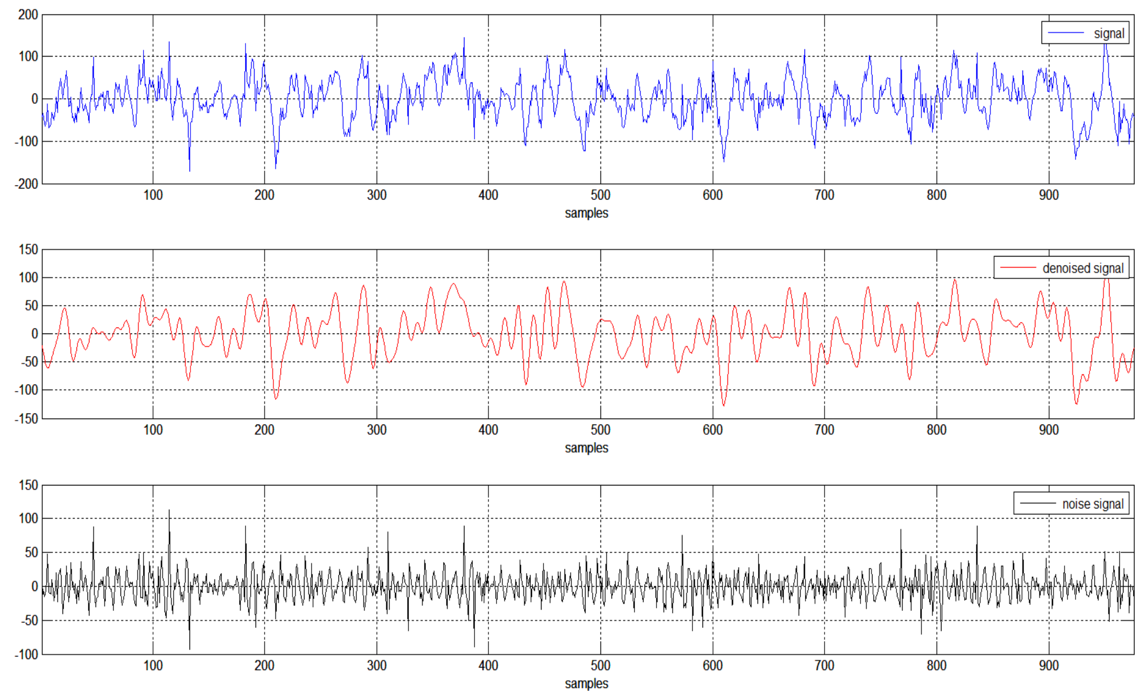
Modified Singular Spectral Analysis (MSSA)

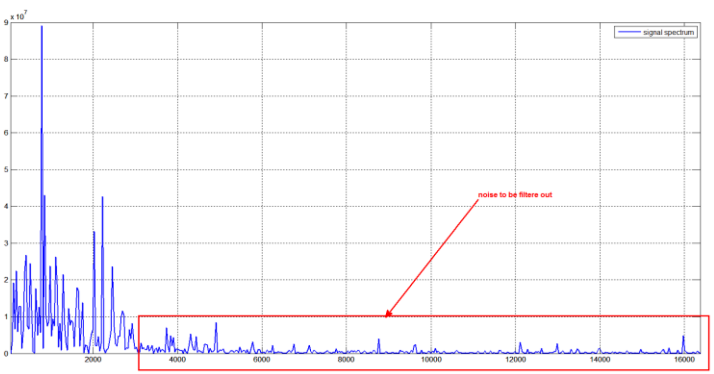
(MSSA) as an alternative to traditional digital filtering methods.

Example



signal to be smoothed





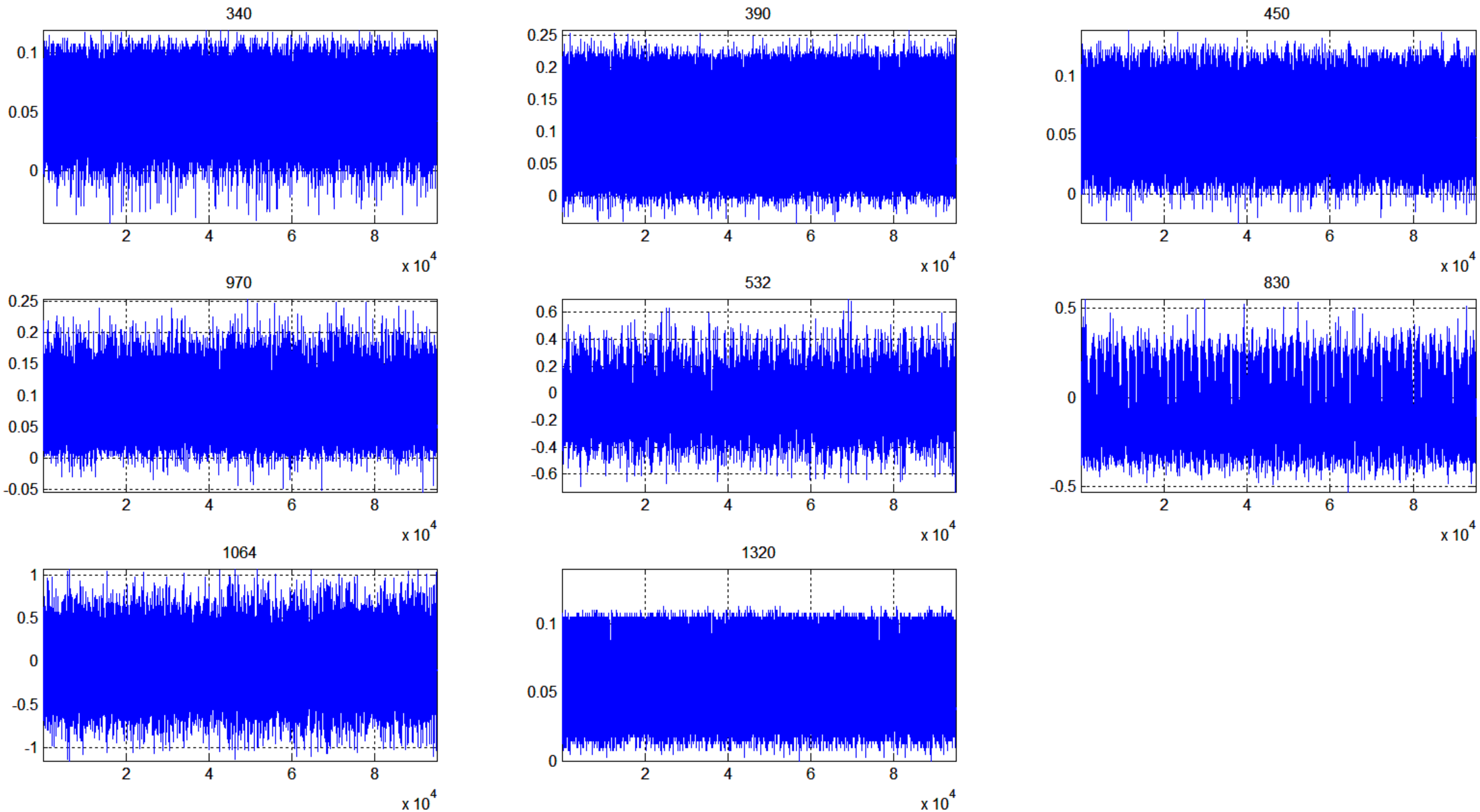
signal spectrum

❑ signal ❑ de-noised signal ❑ noise

Laser Process Monitoring – signal analysis

Modified Singular Spectral Analysis (MSSA)

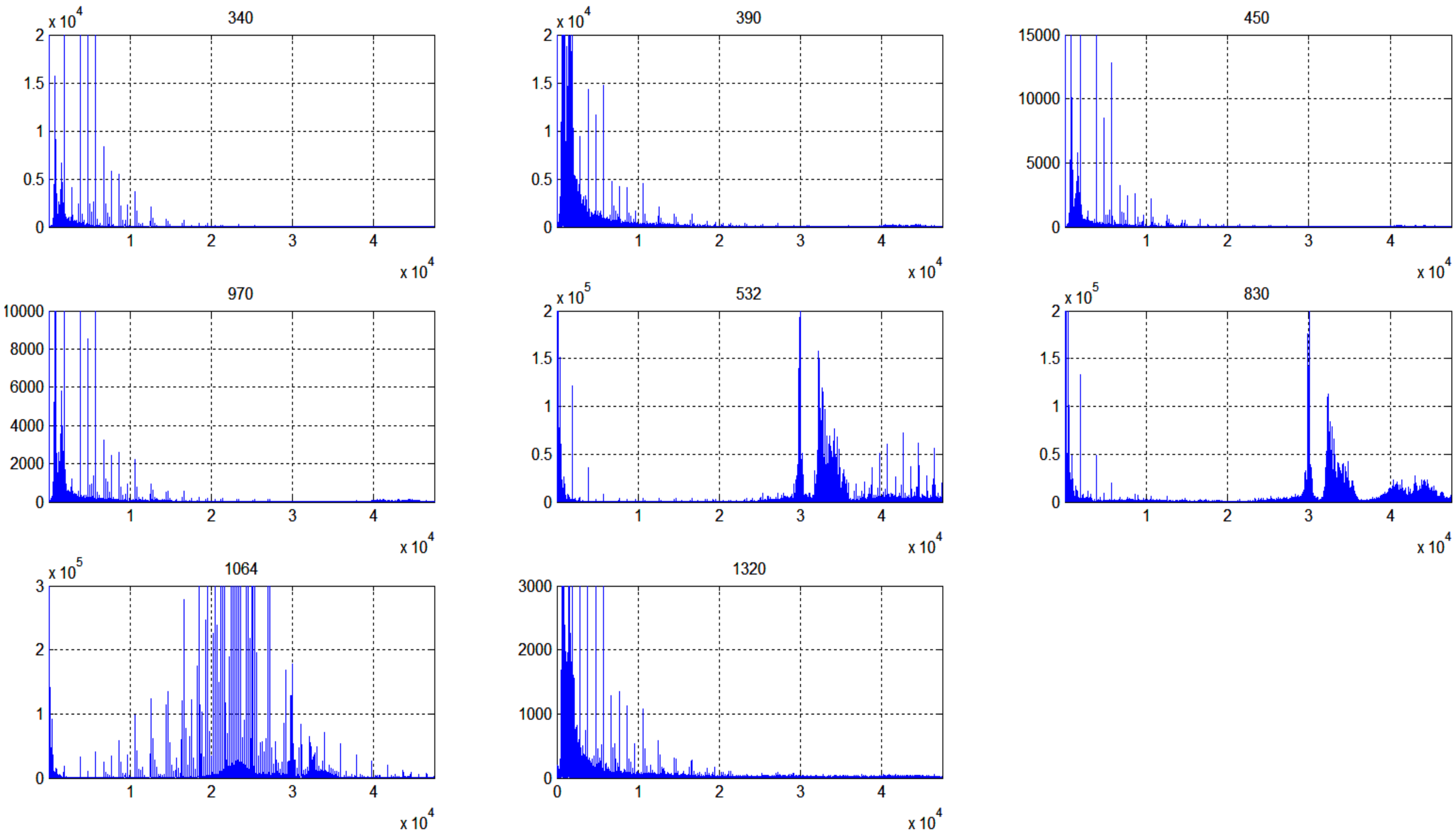
Inco\P0118_const_power



Laser Process Monitoring – signal analysis

Modified Singular Spectral Analysis (MSSA)

Inco\P0118_const_power



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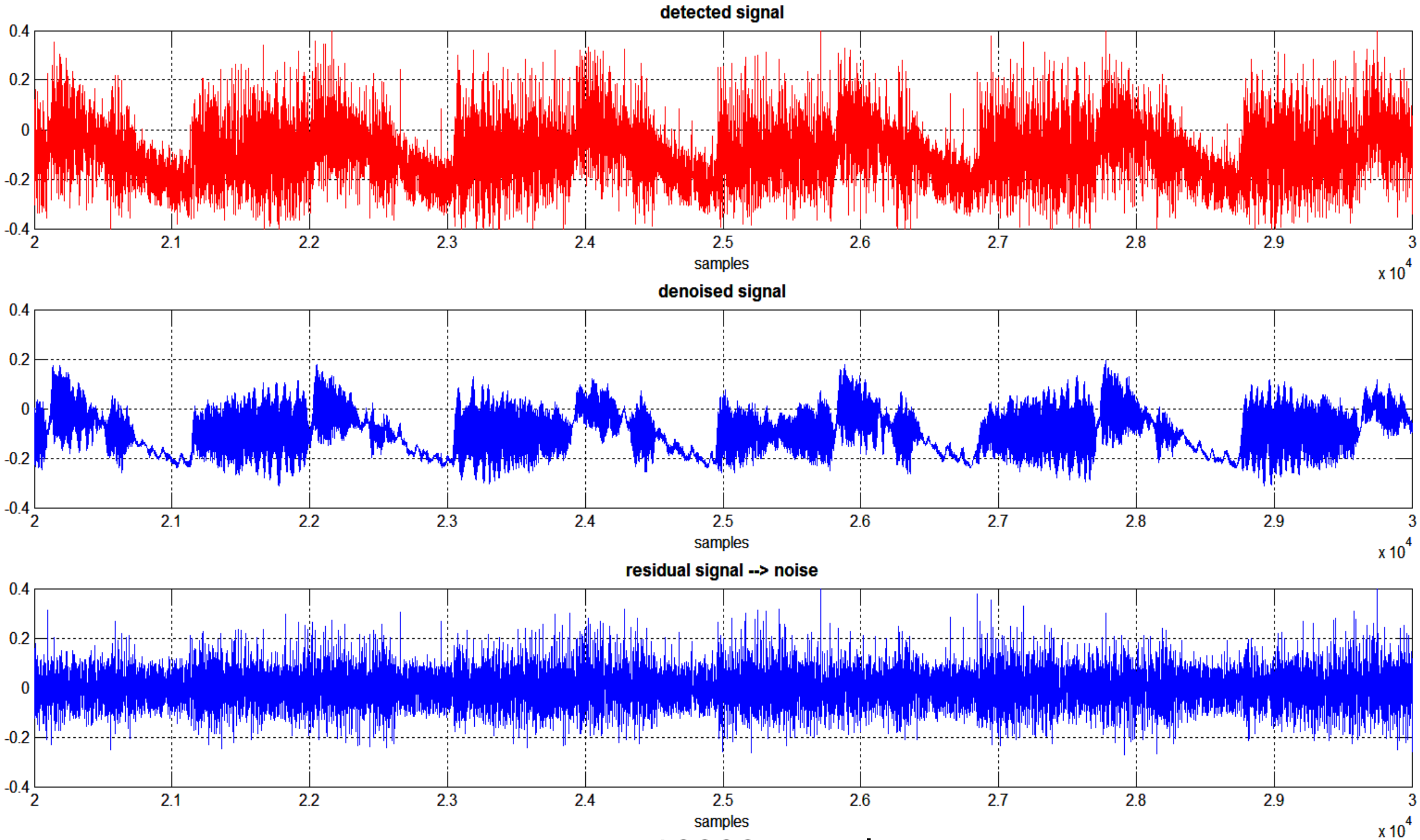
Laser Process Monitoring – signal analysis

Modified Singular Spectral Analysis (MSSA)

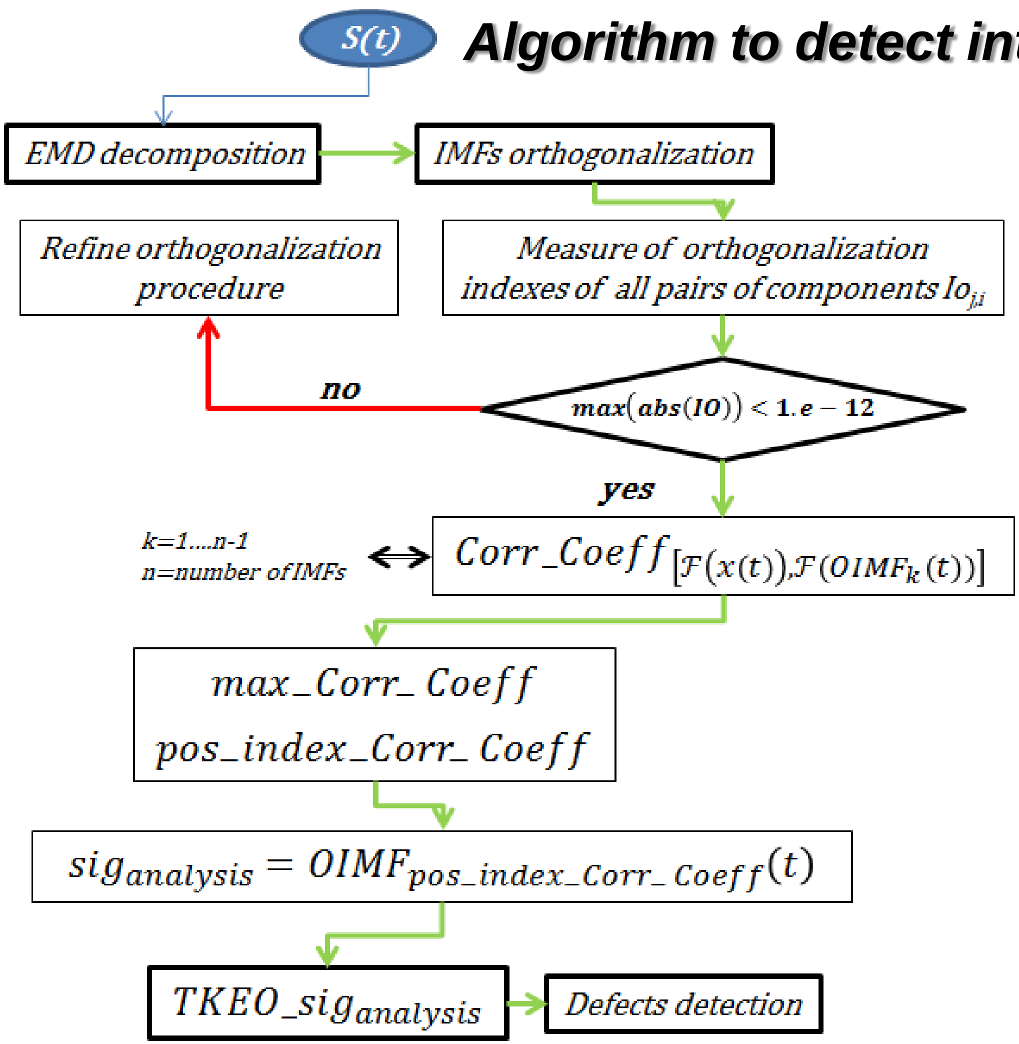


zoom – 10000 samples

Laser Process Monitoring – signal analysis

Orthogonal Empirical Mode Decomposition (OEMD) theory coupled to the Teager Kaiser Energy Operator (TKEO)

Algorithm to detect internal pore formation

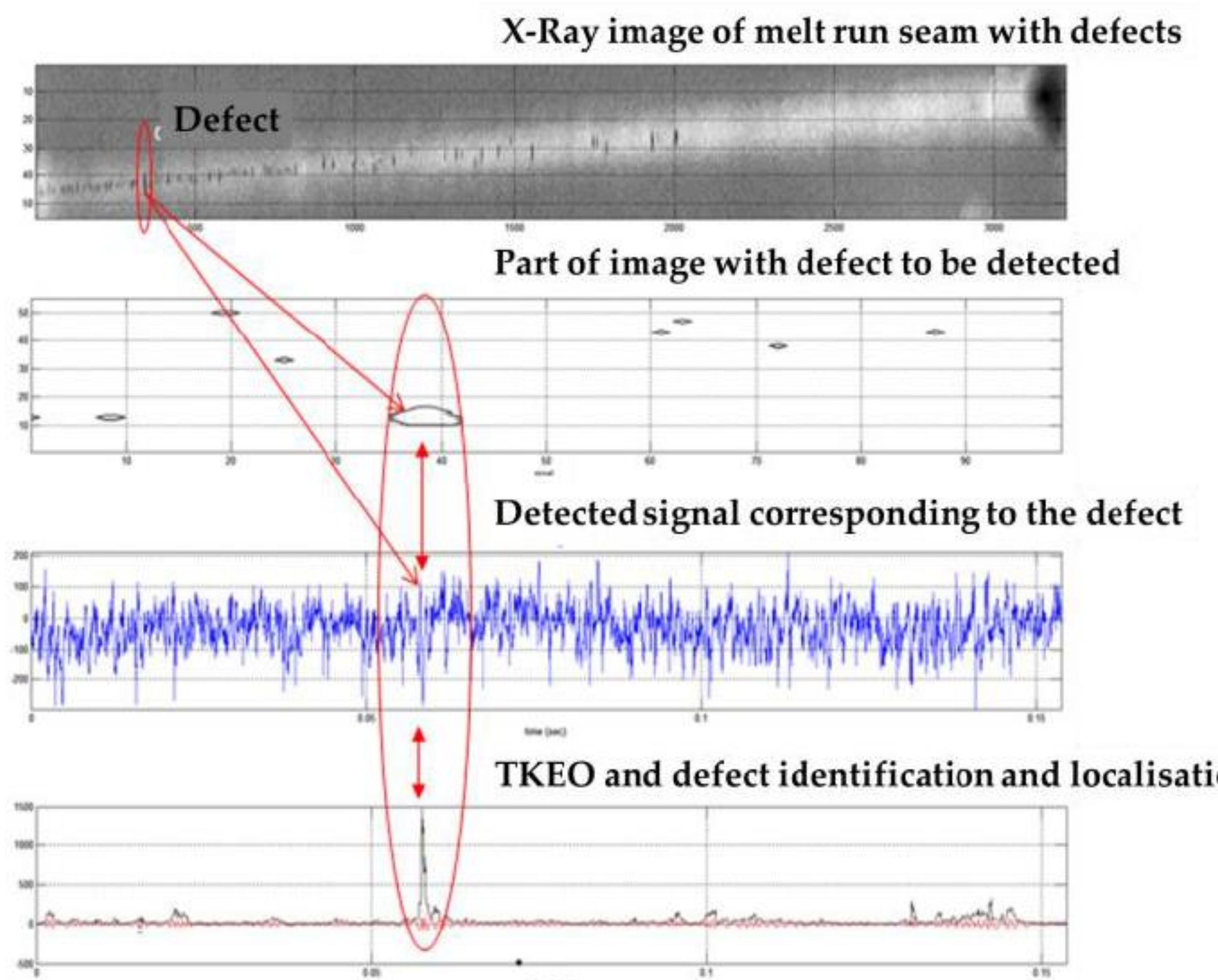


- **Ni 718 – BoP**
- **1msec to acquire 1024 data**
- **For example, for a 5sec signal ~0.5sec are required to receive feedback on any porosity within the weld**
- **Almost real time**

Laser Process Monitoring – signal analysis

Orthogonal Empirical Mode Decomposition (OEMD) theory coupled to the Teager Kaiser Energy Operator (TKEO)

OIMF to correlate photodiode signal data to pores occurring within a melt run in nickel 718 alloy



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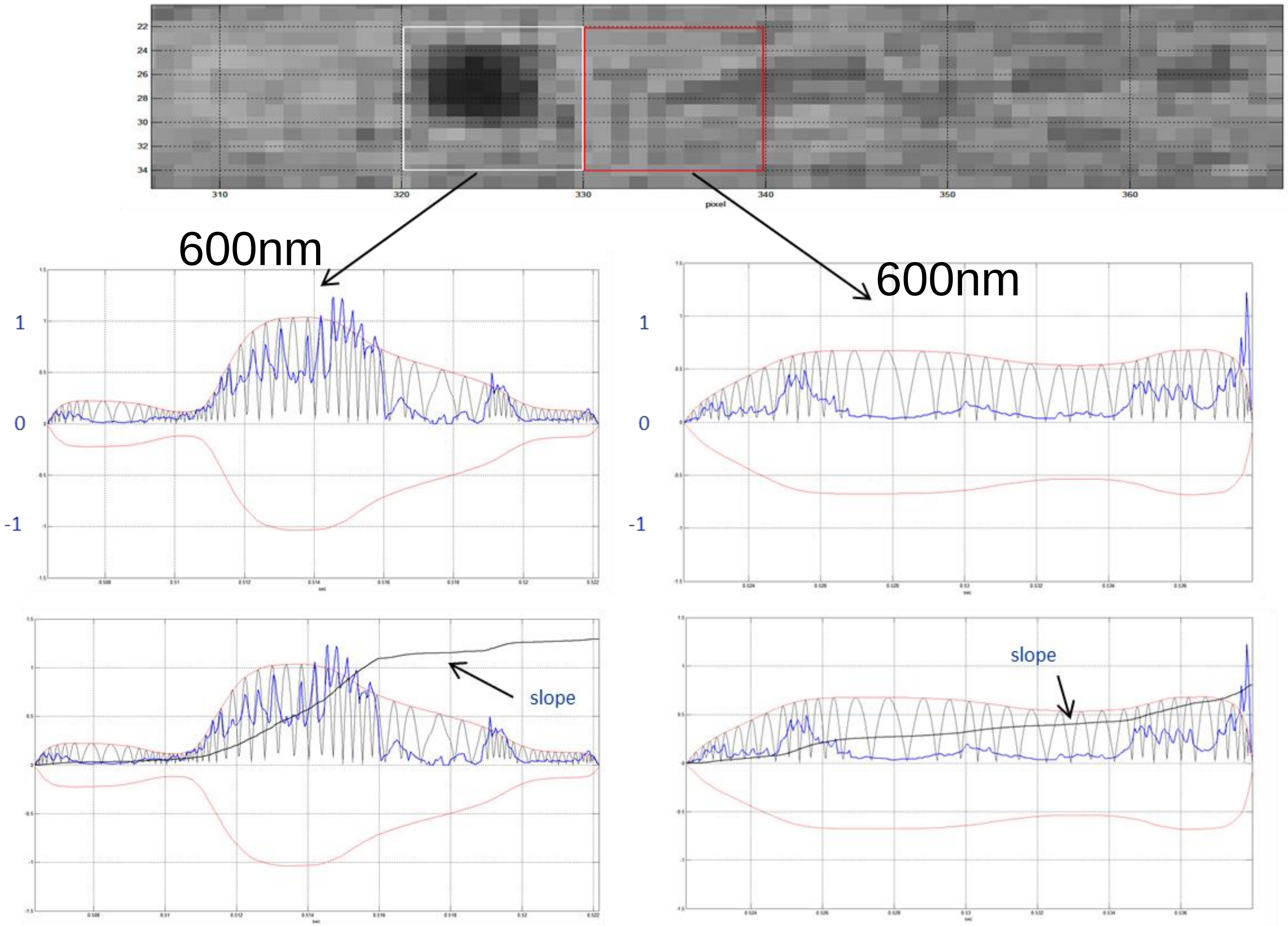
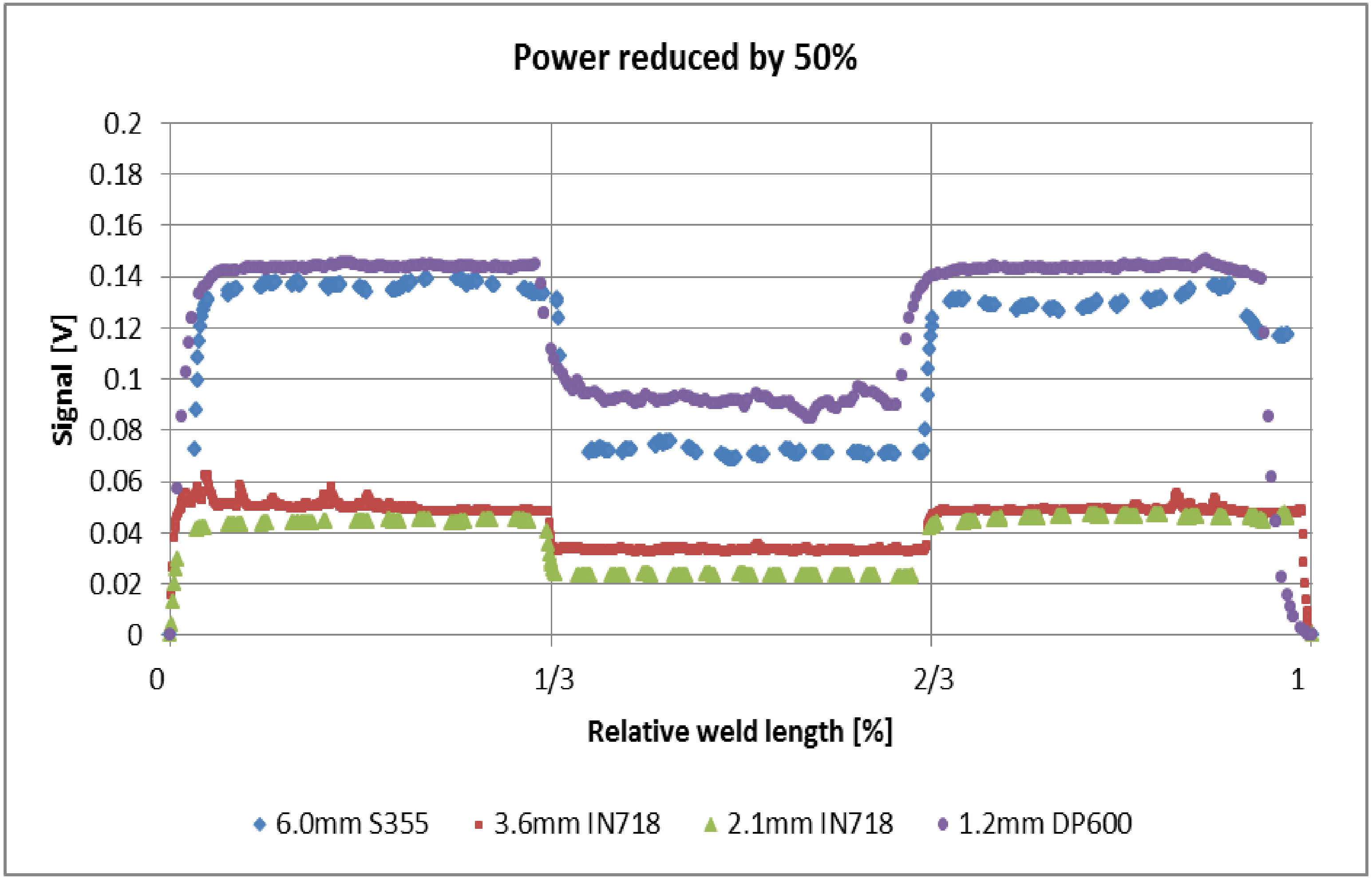
Results – Photodiode Sensor

Internal porosity **Ni 718 – BoP**



- The OEMD theory decomposes the signal into a set of band-limited functions and allows the extraction of instantaneous information from the signal
- The TKEO estimates the instantaneous frequency and amplitude of the signal

Results - In-fibre Built Photodiode Sensor



Incorrect laser power only
(inferred through back-reflected radiation)

Summary and Conclusions

- The low coherence interferometry technique has been proven capable of monitoring keyhole depth in partial penetration welds, in both In 718 and DC01.
- For full penetration welds, keyhole geometry may have an influence on the consequent possibility of measuring keyhole depth
- This finding may lead to an extended application of the IDM sensor, on full penetration welds under certain conditions
- Photodiodes monitoring, in either visible or NIR emissions can be used to infer changes in terms of weld penetration depth, lost of power, occurring weld contamination and joint gap
- For internal porosity, no correlations between the location of pores and the corresponding raw signals from photodiodes could be established
- On the other hand, the photodiode acquisition and data elaboration method, based on the OEMD theory, has been demonstrated to be successful