Process Monitoring & Control - Various Approaches for Different Applications

ICALEO 2009 – Laser solution short courses
No.3, Nov 4 2009

• Industrial laser use and increased degree of automatization
• Phases of the sensor development – from the basics to the actual state-of-the-art

Topics

- Industrial materials processing with lasers - overview
- Motivating forces for on-line process control
- Physical fundamentals
- Examples for industrial process control in laser materials processing
- Novel developments
- Résumé and outlook
Industrial materials processing with lasers

- Forming
  - Bending/straightening
  - Manufacturing
  - Colouring/deposition
  - Rapid prototyping

- Joining
  - Brazing
  - Soldering/thermal welding
  - Repair/reclamation

- Machining
  - Cutting
  - Drilling
  - Scribing/marking
  - Cleaning

- Surface engineering
  - Surface alloying/cladding
  - Surface melting/tempering
  - Surface amorphization
  - Surface hardening/hastening

Green boxes indicate laser processes with industrial on-line process monitoring/ control

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- Résumé and outlook
Motivating forces for on-line process control

Enhancement of the profitability through cost reduction for post weld analysis, post-treatment and machine maintenance

Enhancement of the customer satisfaction through increase in quality of the delivered products

Creation of competitive advantages through documentation of the manufacturing process and increased security in manufacturing

Motivating forces for on-line process control

Quality Assurance in Mass Production
- zero failure tolerance
- 100%-Documentation
- traceability of bad welds

Cost Efficiency
- immediate discharge of bad parts
- no further processing of bad parts, no consumer recalls
- continuous optimization of the process
- reduction of the reject rate
- trend analysis and visualization of warning signals
- avoid production downtimes
- quality assurance within the process cycle
- reduction of visual and destructive testing

Man Machine Interface ( MMI)
- simple graphical user interface (GUI)
- simple integration to the laser machine
- remote service / via Internet
- easy maintenance
- integration in Quality Maintenance system, i.e., ISO 9000

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Conduction welding

The specimen gets heated up to welding temperature. The penetration depth is limited by heat conduction.

Deep penetration welding

Beyond threshold intensity, a vapor capillary (keyhole) is formed, which deeply penetrates the specimen. The laser beam led within this capillary. The melt pool is formed by the capillary which moves through the specimen. When talking about laser welding usually deep penetration welding is meant.

Physical fundamentals

General features of a deep penetration weld – process output phenomena

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Commonly used types of detectors</th>
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<tbody>
<tr>
<td>e.r. electromagnetic radiation</td>
<td>Photo diode (UV, VIS), camera</td>
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<tr>
<td>coaxial detector</td>
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<td>lateral detector</td>
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<td>workpiece surface</td>
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<td>melt pool</td>
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<tr>
<td>plasma radiation</td>
<td>Photo diode (VIS, IR), camera</td>
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<td>laser</td>
<td>microphone</td>
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<tr>
<td>back scattered laser radiation</td>
<td>Charge-collecting device</td>
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<td>temperature-radiation</td>
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Thermo physical Properties (parent material)

- Absorptivity (ability to initiate keyhole welding)
- Melting point (relates power level to weld speed)
- Surface tension (ability to form a weld joint, influences undercut)
- Thermal conductivity (affects weld speed)
- Thermal diffusivity (affects weld size)
- Vapour pressure (affects stability of keyhole)
- Viscosity (affects stability of keyhole)
- Loss of alloying elements

Process Parameters (Equipment configuration)

- Beam alignment (position relative to weld joint)
- Beam diameter (ability to bridge joint gaps)
- Beam focus position (influences weld profile)
- Beam irradiance (power density influences weld speed and depth of penetration)
- Joint geometry (affects allowable gap tolerances)
- Process speed
- Shielding gas (influences plasma plume)
- Degree of process monitoring

Courtesy of Fraunhofer ILT
Physical fundamentals

General features of a deep penetration weld – complex interaction mechanisms

Energy coupling:
- Fresnel absorption
- Plasma absorption
- Heat conduction

Weld pool dynamics:
- Flow around the keyhole
- Surface tension
- Vapour/melt interaction

Physical fundamentals

General features of a deep penetration weld – keyhole dynamics

- Plasma oscillations
  - 1 - 100 MHz
- Instability of vapour-plasma jet due to absorption of laser radiation
  - 0.1 - 5 MHz
- Own acoustic oscillations
  - 50 - 300 kHz
- Capillary-evaporation instability of cavity shape
  - 1 Hz - 10 kHz

Lopota u.a., T.U. St. Petersburg

Physical fundamentals

General features of a deep penetration weld – keyhole dynamics

- Backreflection detector
- Highspeed video camera
  - f = 1500 Hz, Δt = 0.3 s
- Interference filter λ = 523 nm
- Fluorescent screen

ISFW Stuttgart, Osaka University
Physical fundamentals

General features of a deep penetration weld – keyhole dynamics

ISFW Stuttgart, Osaka University

page 16

Physical fundamentals

General features of a deep penetration weld – back reflected laser light

ISFW Stuttgart

page 17

Physical fundamentals

General features of a deep penetration weld – melt pool geometry

Comparison of the calculation results with the mean of experiments:

a) Weld pool length and depth dependent on laser power

b) Correlation between length and depth

Suidnik, W. et al. State University Tula, Russia
Breitschwerdt, S. et al. Daimler AG, Germany

ISFW Stuttgart

page 18
Physical fundamentals

General features of a deep penetration weld – melt pool geometry

Experiments:
- Low-Alloy steel 16MnCr5
- Thickness of 2 to 10 mm
- Laser power from 2 to 5 kW
- Welding speed from 1 to 8 m/min.

Results:
- Weld pool depth is approximately linearly dependent of the weld pool length for varied laser power \( v = \) constant.
- Increased power means larger length and depth.
- Increased speed with \( P = \) constant causes smaller depth with slightly length.

DB-LASIMP and this model simulate the shape and dimensions of the weld pool and the weld cross section in steels and aluminium alloys with the following approach:
- Flow around the capillary – recirculation flow.

Physical fundamentals

General features of a deep penetration weld – acoustic emissions

Air-borne
- Sound is created by the emission of vaporized workpiece material.
- The vapor is ejected with considerable high flow-speed rates which may range up to several hundred meters per second.
- The emerging vapor requires a displacement of the surrounding atmosphere which in turn acts as a source of airborne sound.
- Sound intensity and frequency spectrum depend on the vapor flow rate fluctuations which of course are influenced significantly by the above mentioned dynamics.
- Typical vapor-created sound frequencies are ranging in the audible region - 20 Hz . . . 20 kHz (majority of signal information located in the region of 4.0 – 4.5 kHz).

Workpiece/structure-borne
- The action of the molten pool, formation and collapse of the keyhole all generate structure-borne acoustic emissions.
- Having frequency bandwidths which range up to 200 kHz.
- They may also carry information on treatment quality aspects like crack formation, penetration depth, etc.
- Sound pick-up has to be accomplished inconveniently by transducers coupled firmly to the workpiece.

Physical fundamentals

General features of a deep penetration weld – plasma or metal vapor

R.E. Mueller, W. Duley

Material: zinc coated steel
- Thickness: 1.5mm
- Laser power: 3.5kW
- Spot diameter: 0.6 mm
- Focal length: 190 mm (Nd:YAG), 300 mm (CO\(_2\))
- Support gas: Argon

R.E. Mueller, W. Duley
Physical fundamentals

General features of a deep penetration weld – plasma or metal vapor

Spectrometer measurements

- best fit to the process emissions is Black-Body Radiation curve
- metal vapor is comparable to a hot gas
- temperature between 2000K – 2200K

![Graph](Nd:YAG)

R.E. Mueller, W. Duley

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Physical fundamentals

General features of a deep penetration weld – plasma or metal vapor

Spectrometer measurements

- emission characteristics show a fine emitter
- ionized atoms and free electrons
- metal vapor is comparable to a plasma
- temperatures between 7000K – 11000K

![Graph](CO₂)

R.E. Mueller, W. Duley

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Physical fundamentals

General features of a deep penetration weld – plasma or metal vapor

Temperature at the opening of the keyhole during welding of aluminum and steel with Nd:YAG, CO and CO₂ laser determined by spectrometer measurements

![Graph](Temperature vs Laser wavelength)

Graf, Hügel – Laser in der Fertigung 2009
Physical fundamentals

General features of a deep penetration weld – interaction with the emissions

There is a big influence on the energy transfer to the workpiece by interaction between the laser and the process emissions.

Fundamental characteristic of a plasma – plasma frequency

\[ \omega_p = \frac{\sqrt{n_e e^2}}{\varepsilon_0 m_e} = 10^{13} \text{ s}^{-1} \]

\[ \omega_{\text{Nd:YAG}} = 1.8 \times 10^{15} \text{ s}^{-1} \]
\[ \omega_{\text{CO}_2} = 1.8 \times 10^{14} \text{ s}^{-1} \]

Matsunawa, Osaka Univ.

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Physical fundamentals

General features of a deep penetration weld – conclusions

**CO\(_2\)**

A partially ionized plasma with a temperature between 7000 and 11000K can be expected under cw CO\(_2\) laser welding, with its shape characteristics changing depending on the gas employed as a plasma control mechanism. As widely recognized in the literature, helium proved the most effective gas to achieve a higher penetration weld and narrower heat affected zones.

**Solid state laser radiation – e.g. Nd:YAG**

A plume consisting of a high-temperature (over 2000K) thermally excited gas can be expected for cw Nd:YAG laser welding, with its shape characteristics changing depending on the gas used as a control mechanism for the plume. At low welding speeds, argon proved the most effective gas to achieve higher penetration welds, perhaps due to its higher momentum effect when interacting with the plume.

It has been demonstrated that the ionization potential of the gas side jet in Nd:YAG laser welding does not have the same importance as in CO\(_2\) laser welding, although other properties of the gas could play a role in the interaction with the plume.

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Physical fundamentals

General features of a deep penetration weld – conclusions

Resulting effect on the focus properties based on the interference of the CO\(_2\) laser beam with the laser induced plasma.

Graf, Hügel – Laser in der Fertigung 2009
Physical fundamentals

General features of a deep penetration weld – conclusions
Scattering of the laser beam in the emitting metal plume
By the use of a special nozzle (MDE nozzle by TRUMPF) the scattering losses can be reduced

By courtesy of TRUMPF, patent pending

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Industrial process control

Pre process:
- Position of joint partners / gap
- Gap width
- Position TCP / seam

In process:
- Welding depth / root fusion
- Cross section of connection
- Holes
- Dropouts
- Seam position
- Pores
- Spillings

Post process:
- Cracks
- Holes / pinholes (open pores)
- Insufficient fill
- Undercut notches
- Face / root reinforcement
Industrial process control

Sensor design for in-process monitoring – solid state and CO₂ laser applications

External sensors
- plasma / plume
- temperature
- P/T combined

Sensors can be adjusted to certain areas of the melt pool and welding area.

Internal sensors
- plasma / plume
- temperature
- back reflection
- laser power
- protected against contamination
- no interference with workpiece
- special sensors for the integration to beam source – beam path
- also suitable for scanners

Integrated sensor unit:
- plasma / plume
- temperature
- laser back reflection
- laser power
- camera (observation)
- linear drives (y, z) for seam tracking
- cover slide monitor
- Cross jet
- seam tracking camera
- coaxial shielding gas supply

Processing head YW52
Industrial process control

Sensor design for in-process monitoring – solid state and CO₂ laser applications

Use of the External Detectors at the Roof Welding of the 520-540 series at BMW AG

T-Detektor: 900nm - 1900nm
P-Detektor: 250nm - 400nm

Use of the Internal Detectors on a Tailor Welded Blank Application

T-Detektor: 1200nm-1900nm
P-Detektor: 400nm-600nm
R-Detektor: 1064nm

Use of the YW50 with fully integrated sensors on a Tailor Welded Blank and Hybrid Welding Application

T-Detektor: 1200nm-1900nm
P-Detektor: 400nm-600nm
R-Detektor: 1064nm
Industrial process control

Sensor design for in-process monitoring – solid state and CO₂ laser applications

Optimum detection window for monitoring device to get an undisturbed view on the workpiece surface
Industrial process control

Sensor design for in-process monitoring – solid state and CO₂ laser applications

Process: CO₂ (3kW, 3 m/min)
Material: 16MnCr5

- Normal
- Gap
- Butt joint: different thickness
- Butt joint with filler material

11/09 MKH ICALEO Laser solution short course

page 43

courtesy of Daimler AG

11/09 MKH ICALEO Laser solution short course

page 44

Industrial process control

Sensor design for in-process monitoring – solid state and CO₂ laser applications

Laser power loss
Misalignment

Process: CO₂ (3kW, 3 m/min)
Material: 16MnCr5

11/09 MKH ICALEO Laser solution short course

page 45
Coaxial mounted camera: part of the closed beam path
Spatial resolved monitoring of the keyhole surrounding melt pool

Welding defects
- Missing seam length
- Lack of fusion
- Incompletely filled groove
- Incomplete penetration
- Cracking

Errors, relevant for the given application, can be detected:
- Beam Position
  → form analysis
- Defocusing
  → near keyhole melt pool intensity
- Gap
  → intensity behind near keyhole
Laser Power
  → near keyhole melt pool intensity

Sensor design for in-process monitoring – solid state and CO₂ laser applications
Lap joint configuration – coated steel
- Good Weld
- Not sufficient penetration
- gap

courtesy of Daimler AG
Industrial process control

Sensor design for in-process monitoring – solid state and CO₂ laser applications

Butt joint configuration

welding direction

 Courtesy: IFSW Stuttgart

Industrial process control

Sensor design for in-process monitoring – solid state and CO₂ laser applications

Partial penetration

Full penetration

Material: D77, 15 mm, laser power 3 kW, Power SW 800, spot size 10 mm, clad speed 50 m/min

Industrial process control

Sensor design for in-process monitoring – strategies in combining technologies

- Combination of camera and photodiode based sensor technology
- Coaxial interface for photodiode based and camera based sensors: Standard camera interface
- Combination and correlation of sensor signals

Camera device

Photodiode sensors
Industrial process control

Camera based sensors in solid state remote laser welding

CMOS Camera
Path of the process light back to the camera

Industrial process control

Sensor design for in-process monitoring – strategies in combining technologies

Post In Pre

Courtesy Trumpf Laser

Industrial process control

Methods in signal processing

- Tolerance bands
- Fuzzy-Logic
- Neural networks
- Multivariate analysis methods
  - regression analysis
  - variance analysis
  - contingency analysis
  - discriminant analysis
  - conjoint analysis
- Measurement
- Wavelet analysis
Industrial process control

Methods in signal processing – application sample powertrain gear part

- Trumpf CO₂ Laser 4.8 kW
- Butt weld with 2 steps:
  1. First pass for pre-heating
  2. Second pass for welding

Indicators:
- Sensitivity of plasma signal: e.g. focal position, laser power
- Sensitivity of temperature signal: e.g. lateral offset

Left weld signature is OK
Right weld signature is NOT OK

0.25 mm lateral offset and focal position

Plasma signal change due to focal position or laser power
Temperature signal change due to lateral offset of 0.25 mm

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Novel developments

World premiere – camera based closed loop control of full penetration welding

Approach:

Use of a special camera (CNN – Cellular Neural Network) and an application specific algorithm to detect and control the existence of the full penetration hole.

World premiere – camera based closed loop control of full penetration welding

Control of full penetration with varying feed rate by adjusting laser power.

Increased failure detection reliability through illuminated interaction zone

Typical setup and effect for the laser cutting process.
Novel developments

Increased failure detection reliability through illuminated interaction zone
Steps in image processing to achieve information on weld pool geometry

CMOS camera
Illumination (diode laser 150mW @ 830nm)
Beam splitter
Dichroitic mirror
Processing laser

Novel developments

Increased failure detection reliability through illuminated interaction zone
Optional bright field illumination for non metal laser welding, e.g. polycarbonates

PC, 2mm+2mm
22 W, 3 m/min
500 Hz

PC, 2mm+2mm
20 W, 3 m/min
500 Hz

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Résumé and outlook

Equipment considerations

- Ensure that the detectors have a sufficient acquisition rate to provide the monitoring resolution required.
- Ensure that the appropriate monitoring locations and field of view are established.
- The more process input parameters of the laser weld are monitored, the better the confidence limit and reliability
- Data acquisition software should have sufficient features to establish the benchmark or reference “good” weld signature and determine a weld failure

Process considerations

- Program for documentation of the weld set that establishes the reference weld signatures.
- Program for interpretation and correlation of collected data to weld quality.
- Program for establishing confidence of weld process monitoring system.
- Maintenance and validation program for equipment/sensors.
- Process drift analysis

Technical innovation considerations

- Use of camera technology will increase the robustness of the detection reliability and the complexity of the total system.
- The process emissions – plasma, plume or hot gas – have an effect on the failure detection which increases the complexity of the image processing algorithms.
- Flexible illumination techniques (application and material dependent) improve the visibility of quality related information (e.g. Measurement of the meltpool geometry based on phase boundary detection).
- Novel camera techniques (high-speed image ratio) make closed-loop control possible.

Personnel considerations

- A champion is required to establish and review the data collected and the parameters by which the weld quality is assessed by the monitoring equipment.
- Training is crucial.

Quality assurance

Defective parts reduce productivity and increase manufacturing costs. Sensors that monitor processes and ensure quality are increasingly gaining in importance.

For a long time, sensors were considered to be a luxury that only few users could afford. Today, integrated sensors for process monitoring are a standard feature, even on machines for serial production.

Abstract of: “Laser as a tool” - by TRUMPF
Course #3:
Process Monitoring & Control – Various Approaches for Different Applications

Course Instructor: Markus Kogel-Hollacher

Please rate the following: (circle)

<table>
<thead>
<tr>
<th>Course</th>
<th>Excellent</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
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Would you recommend this course to others in your profession? yes no

What was the strongest feature of the course?

________________________________________________________________________

What was not covered that you felt should have been covered (if anything)?

________________________________________________________________________

What would you like to hear more about next time?

________________________________________________________________________

What was covered that left an impression/impact on you?

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Suggestions & Comments (for this course or courses you would like in the future):

________________________________________________________________________

________________________________________________________________________

Name: (optional)  __________________________________________________________

Please Use Reverse Side for Additional Comments.

Please return evaluation form to the Registration Desk by Thursday afternoon
or fax 407.380.5588 to LIA upon your return home.

THANK YOU!