Fundamentals of pulsed Nd:YAG and fiber laser welding

Laser fundamentals
Elements of a laser welding system
The route to a successful weld
Laser Fundamentals
What is a laser..

- **Light**
- **Amplification by**
- **Stimulated**
- **Emission of**
- **Radiation**

Elements of any laser
- Laser medium
- Pump energy for medium
- A resonator that controls the generation and amplification of the laser
1. Spontaneous emission – the seed

- Pump energy
- Electron
- Time

Excited state

Laser photon

Ground state
Processing fundamentals

• The laser must be focused for materials processing
Elements of a laser welding system
Laser Welding System

Laser
Beam delivery
Focusing head
Process
Tooling & Motion

Elements of a laser welding system:
1. Laser
2. Beam delivery
   - Fiber / mirrors
3. Focusing head
   - Lens
4. Process
5. Tooling & Motion
Welding Lasers

- Pulsed Nd:YAG laser
- Micro welder (<0.02” penetration)
Features of pulsed Nd:YAG welders

- Very flexible
- Highly controllable
- Lowest heat input of any welding laser
- Robust industrially proven
  - Very reliable
  - Many parts field replaceable
- Energy / time share
  - Optimize laser usage, multiple welds per part
- Fiber delivery
  - Locate laser where it's convenient
  - Standard fiber lengths 5, 10 & 20m (longer available)
Welding Lasers

- Continuous Wave (CW) lasers
  - Fiber laser
- Penetration welder (>0.04”)
Features of Fiber laser welders

- Excellent penetration and speed performance
- Efficient welding mechanism
- Fiber delivery
  - Locate laser where it is convenient
  - Standard fiber lengths 5, 10 & 20m (longer available)
- Wall plug efficiency up to 30%
- Energy / time share
  - Optimize laser usage, multiple welds per part
Comparison of pulsed and CW lasers

- Pulsed Nd:YAG lasers
  - Micro spot welder
  - Fine control of weld energy
  - Pulse durations typically 0.1 – 10ms
  - Peak power up to 250 times average
    - 25W laser provides 6kW peak power
    - Average power = heat input, welding speed
  - Large welding spot size (400-600 microns)

- Continuous wave
  - Penetration welder
  - High speed seam applications
  - Power range 1 – 5 kW
  - Peak power is the same as average power

![Pulsed Nd:YAG output diagram](image1.png)

![Continuous wave or gated output diagram](image2.png)
Laser Beam Delivery

Delivering the laser to the workpiece
The laser – where it starts

- Nd:YAG crystal
- Shutters
- Beam coupling to fiber
- Fiber
Fiber Optic Delivery + Focus head

Fiber Optic

CCTV Camera

Focusing Head

Part

Fiber Optic end
Focus head

CCTV Camera

Fiber optic
From laser

Collimating Lens
Focusing Lens
Protective Cover Slide

Working distance

Part
The Route to a Successful Weld

Design for Laser Welding
Defining the requirements of the weld

Materials, Joint geometry, Penetration, Cycle Time

Part tolerances, Fit-up, Laser parameters

The Required Weld
The Required Weld

• What is the purpose of the weld
  – Mechanical / electrical / sealing

• Inspection techniques
  – Weld cross section
  – Pull/peel testing
  – Pressure testing
  – Resistance
  – Hermeticity

• Optimizing penetration requirements
  – Reduce laser size
  – Increase speed
## Material selection for pulsed Nd:YAG Welding

<table>
<thead>
<tr>
<th>Material</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Welding is limited to certain grades such as 6061 to 4047 or 4032, 1050, 1100, 3003 and 5005. High energy levels required to overcome surface reflectivity. Other aluminum alloys should be tested thoroughly for joint design and crack sensitivity.</td>
</tr>
<tr>
<td>Beryllium Copper</td>
<td>Good welds. Alloys containing less copper are best due to reduced reflectivity. A safety hazard exists from the toxic beryllium oxide fumes</td>
</tr>
<tr>
<td>Carbon Steel</td>
<td>Good welds, carbon content should be less than 0.12%.</td>
</tr>
<tr>
<td>Copper</td>
<td>Generally limited to spot welds. High energy levels required to overcome surface reflectivity.</td>
</tr>
<tr>
<td>Hastalloy-X</td>
<td>Good welds</td>
</tr>
<tr>
<td>Kovar</td>
<td>Good welds</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Good welds, slight brittleness.</td>
</tr>
<tr>
<td>Nickel</td>
<td>Good welds</td>
</tr>
<tr>
<td>Phosphor Bronze</td>
<td>Good welds</td>
</tr>
</tbody>
</table>
| Stainless steel   | 304 & 304L produce excellent welds  
316 & 316L are ok provided Cr/Ni ratio is greater than 1.7  
Other 300 series require testing, though 303 should be avoided  
400 series require testing for crack sensitivity.                                                                                     |
| Titanium          | Good welds, gas shielding is key                                                                                                                                                                         |
**Material selection – size of laser & process speed**

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative weld energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Alloy Steel</td>
<td>1</td>
</tr>
<tr>
<td>Titanium</td>
<td>1.5</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>1.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>3.5</td>
</tr>
<tr>
<td>Copper</td>
<td>5+</td>
</tr>
</tbody>
</table>
Material selection

• Stick to your recommended vendors!
Material plating

- **OK**
  - Nickel coated
  - Gold coated (to around 1 micron)
  - Electrolytic process
  - Zinc (weld spatter)
  - Tin (weld spatter)

- **Bad**
  - Thick plating
  - Electroless plating process

Material generally welds better without plating
Joint Geometry & Fitup

- Select for efficiency
  - Tolerance to fit-up, speed, strength
- For best results - NO GAP between parts!
Butt weld

- Gap allowed around 10% of beam diameter
Lap weld

- Gap allowed around 25% of beam diameter
Fillet weld

• Gap allowed around 15% of beam diameter
The Process

Fiber and focus head selection
Selecting Fiber and Focus head for Application

Fiber Optic end

Spot size = core diameter of delivery fiber x focus lens collimator lens
Size of Parts

- What makes sense, size to component & joint

Laser

Spot size too large
Depth of focus

75mm Focal length

Small spot size, small vertical tolerance

125 mm Focal length

Large spot, large vertical tolerance
**Working distance**

- Accommodation of tooling / peripheral equipment
Fit up tolerances

- Gap between parts & positional variance

Good fit-up & position

- Laser
- 0.02” spot size

Poor fit-up

- Laser
- 0.04” spot size

Poor position repeatability

- Laser
- 0.04” spot size
Weld stability

- Increasing spot size increases weld stability
- Aluminum key material
  - Disturbances in weld pool are magnified by low viscosity
  - Large spot size = large melt pool = more damping effect
    - Throwing a stone into a bigger pond!
Summarizing the optics selection

• Define required spot size
  – Select focus lens for working distance
  – Select fiber core diameter for power (pulsed Nd:YAG laser only)
  – Select collimator to fit
The Process

Laser parameters
Heating with a laser – The big picture
Welding modes

CONDUCTION

- Low energy density heat source relies on conduction from the surface
- Shallow welds
- Large heat input

KEYHOLE

- High energy density heat source such as laser welding produce an internal heating effect by the creation of a vapor filled element know as a keyhole welding to increase penetration
- Narrow deep welds
- Small heat input
Welding with a laser - Welding modes

Conduction

Partial Keyhole

Full Keyhole

Increasing laser power density
Pulsed Nd:YAG Laser Parameters

- **Peak Power (kW)** – Main parameter that determines weld penetration.
- **Pulse Width (ms)** – Effects width and penetration
  - **Pulse Energy (J)** – Peak power x pulse width.
Effect of Peak Power

- Controls penetration depth
  - Too high causes porosity & drilling

Increasing peak power

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>1kW</th>
<th>1.5kW</th>
<th>2kW</th>
</tr>
</thead>
</table>
Effect of Pulse width

- Increases width and depth
Effect of Peak power & pulse width

Material: Titanium (0.02” spot size)

<table>
<thead>
<tr>
<th></th>
<th>0.25 kW</th>
<th>0.5 kW</th>
<th>0.75 kW</th>
<th>1.0 kW</th>
<th>1.25 kW</th>
<th>1.5 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2ms</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>4ms</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
<td>7ms</td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
<td><img src="image16" alt="Image" /></td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
</tr>
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0.02”
Seam Welding Laser Parameters

- Pulse Repetition rate (Hz) – number of pulses that the laser fires per second
- Pulse overlap (% of weld diameter) – how much subsequent pulses overlap
  - Average power (W) - peak power x pulse width x repetition rate.

Pulse repetition rate or Frequency = 1/ pulse period
Overlapping spots

- **Overlap %** - function of speed, pulse repetition rate and weld spot diameter
- **Rule of thumb settings**
  - 60-70% spot overlap for strength
  - 80-90% spot overlap for hermaticity
  - Small laser can seam weld, just slower
Sizing the laser

• Lasers are described in average power
  – A 400W laser can provide 400W average power

  – Example: Weld requires 4kW at 5ms = (4kW x 5ms) = 20J
    • How fast can we pulse with a 400W laser?
    • 400W / 20 J = 20 Hz (20 times per second)

  • Welding speed = (1 - overlap) x spot size x frequency
**Fiber Laser Parameters**

- Average Power (kW) – Main parameter that determines weld penetration.
- Spot size selection important
Power vs Speed for Fiber Laser

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>40ipm</th>
<th>60ipm</th>
<th>80ipm</th>
<th>100ipm</th>
</tr>
</thead>
<tbody>
<tr>
<td>3kW</td>
<td><img src="3kW_40ipm.png" alt="Image" /></td>
<td><img src="3kW_60ipm.png" alt="Image" /></td>
<td><img src="3kW_80ipm.png" alt="Image" /></td>
<td><img src="3kW_100ipm.png" alt="Image" /></td>
</tr>
<tr>
<td>5kW</td>
<td><img src="5kW_40ipm.png" alt="Image" /></td>
<td><img src="5kW_60ipm.png" alt="Image" /></td>
<td><img src="5kW_80ipm.png" alt="Image" /></td>
<td><img src="5kW_100ipm.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Single Mode and Multi Mode fiber lasers; the importance of spot size

- 500W single mode laser
- 1 kW multi mode laser

- 1.5mm thick steel at 300ipm with 30 micron spot size
- 1.5mm thick steel at 40ipm with 200 micron spot size
Role of Shielding gas for pulsed Nd:YAG laser

- Prevents oxidation
- Produces aesthetic shiny weld
- Required for titanium, inconel,
- Laminar flow

Off axis diffuser

Part Travel

Argon cover
No cover
Role of Shielding gas for fiber laser

- Prevents oxidation
- Welding plume suppression
- Active gas pressure

![Diagram of laser welding process]

Off axis gas jet

Welding plume

Part Travel
Laser Process & Integration features

- Real time power feedback
- Energy/Time share – multiple outputs
- Excellent pulse to pulse stability
- Pulse Shaping (Fix and Flex Modes)
- Laser Power Ramping (seam welding)
Internal Laser Power Feedback at Work

- All Miyachi pulsed Nd:YAG and fiber lasers
- Same power delivered to workpiece every time, all the time

Supplied pulse

Demanded pulse
The Laser - Time Share: Welds Sequentially
The Laser - Time Share: Welds Sequentially

10 Watts

100% Mirror

10 Watts

0 Watts

100% Mirror

10 Watts

100% Mirror
The Laser - Energy Share: Welds Simultaneously

10 Watts

50% Mirror

100% Mirror

5 Watts

5 Watts
Pulse Shaping

- Pulse Shaping
  - FIX Mode
    (3 segments)
  - FLEX Mode
    (20 segments)

- Applications; welding aluminum, crack alleviation
Laser Power Ramping

- Available in all LW50A – LW600A Lasers, FL fiber lasers.
- Example of Power Ramping:

Without Power Ramping

A series with Power Ramping
Tooling & Motion
Tooling (you can’t weld air)

• Tooling functions
  – Clamp parts with minimal gap at the weld interface
  – Consistent positioning under laser
  – Flexibility
  – Ease of use
  – Heat sink

• Modeling
Part Alignment & seam tracking - Nominal Values

Variance in:
- X direction is critical
- Y is travel direction
- Z is forgiven due to large focusing tolerance

Includes Part Tolerances

+/-.003”

+/-.010”
Motion

- How many axis are required to weld the part(s)
- How accurate does the positioning need to be
- How fast do the stages need to move
- Does the laser or the part move
Putting It All Together
Process Requirements - define the required weld
Materials, joint geometry, cycle time, part fit-up, part tolerances

Laser Settings:
- Peak Power / Pulse Energy
- Pulse Width
- Pulse Repetition Rate

Beam Delivery:
- Fiber Core Diameter
- Focus Head Collimating Lens
- Focus Head Focus Lens

Average Power, Spot Size, Power / Energy Density, Spot Overlap (Seam Welding)

A FULLY UNDERSTOOD & CONTROLLED WELD!!!!!
Welding in Production

• Bench mark weld
  – Visual, penetration, sensitivity
• Standardize set-up procedures
• Power checks
• Troubleshooting
  – Work from the material backwards